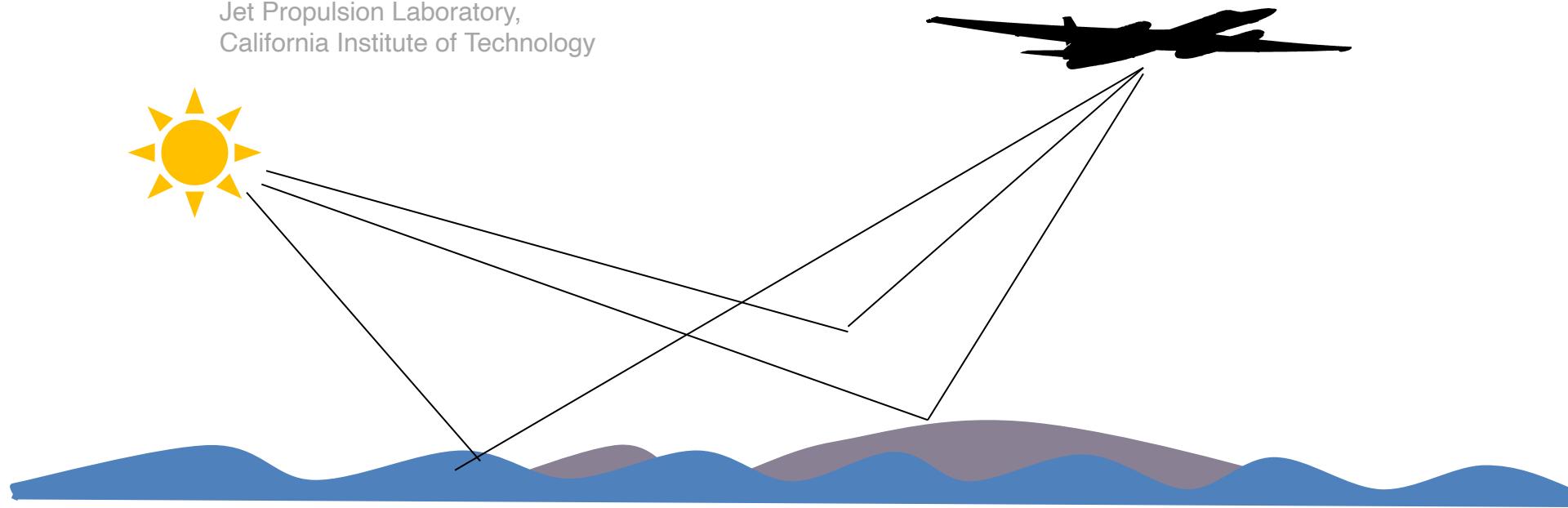


Bayesian methods for remote coastal measurement using imaging spectroscopy

David R. Thompson

Jet Propulsion Laboratory,
California Institute of Technology



Jet Propulsion Laboratory
California Institute of Technology

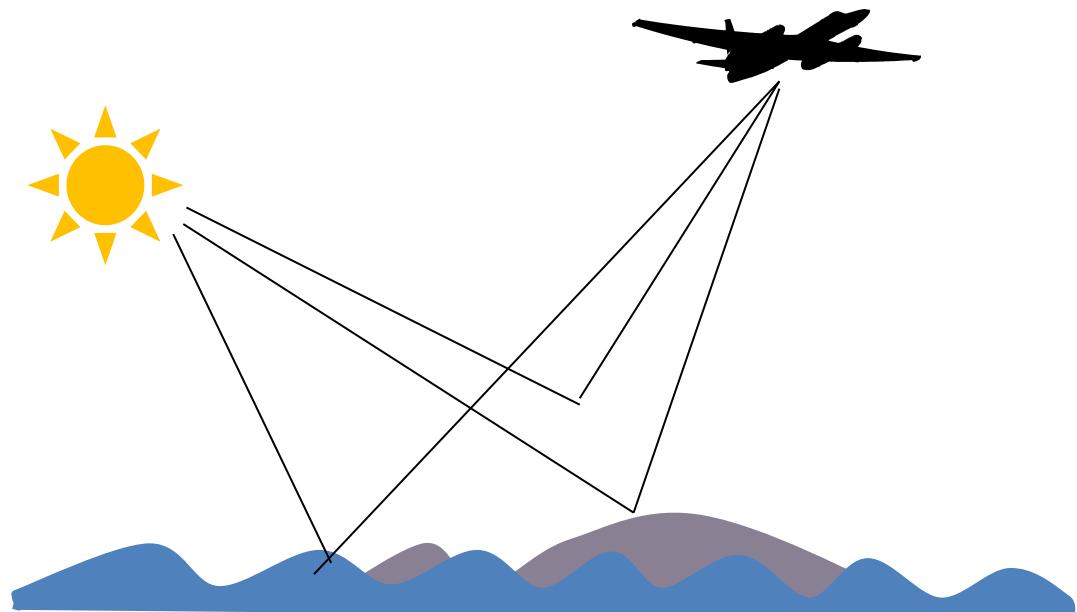
Copyright 2019. All Rights Reserved. A portion of this research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. NASA programmatic support through ESTO and Terrestrial Ecology programs is gratefully acknowledged.
Image credit: NASA

Agenda

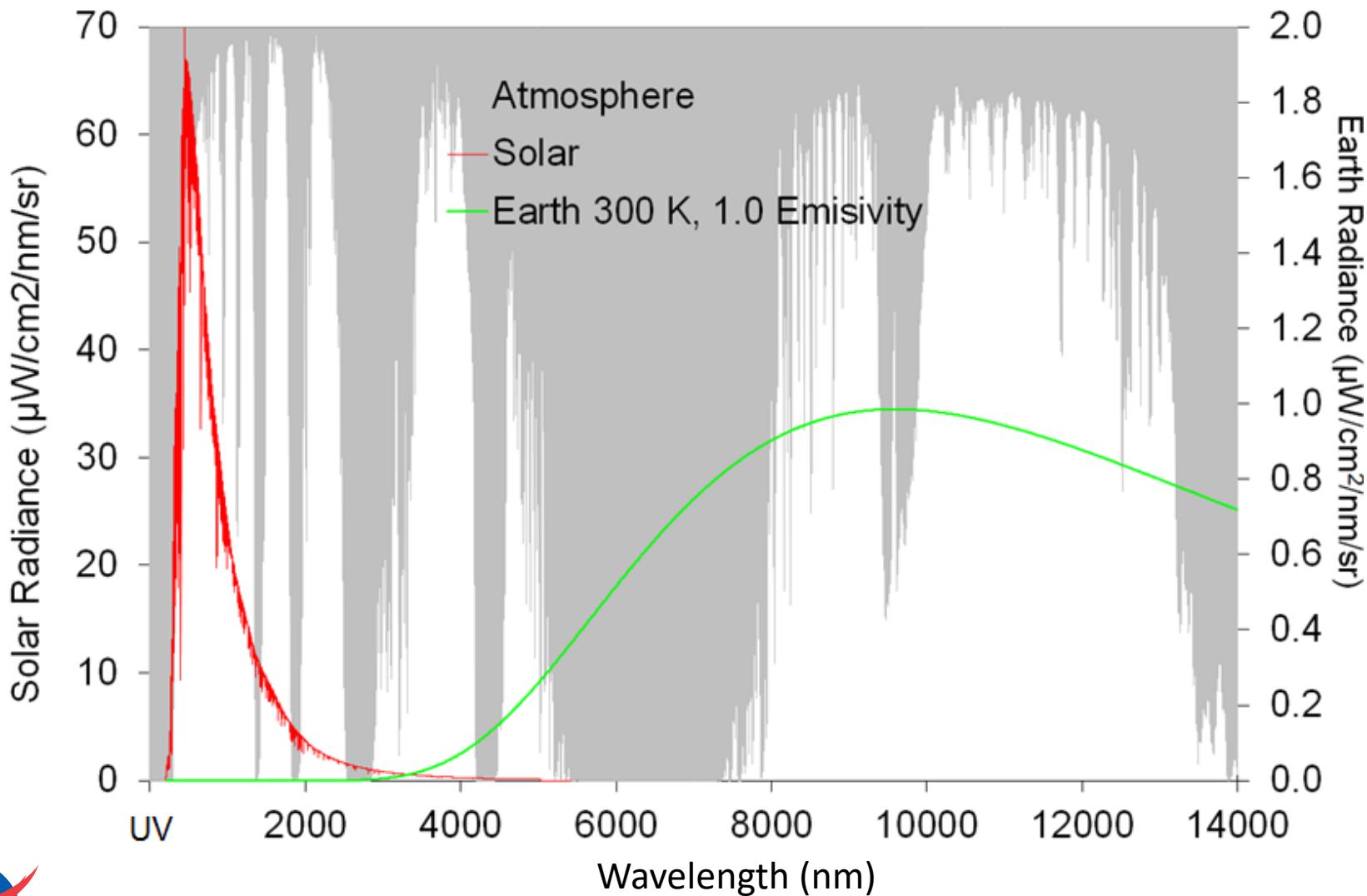
Algorithms

Case Studies

Science & Future Missions

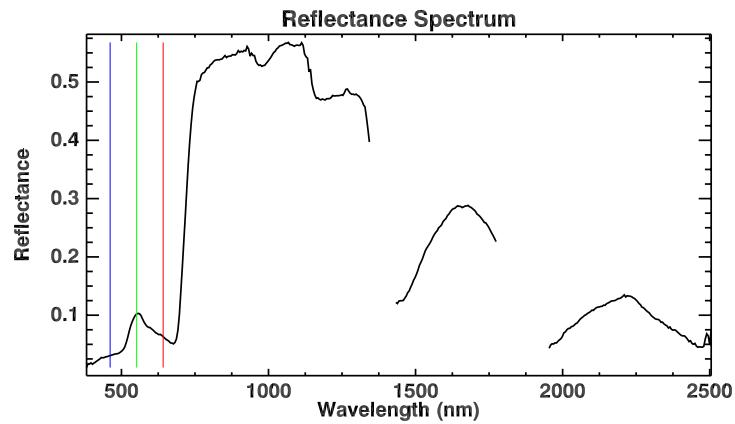
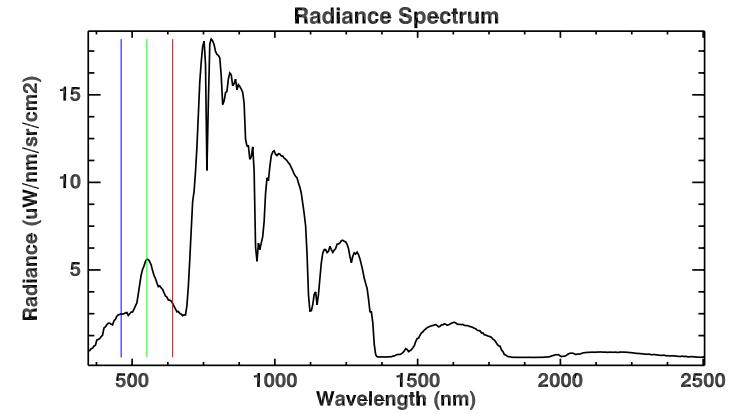
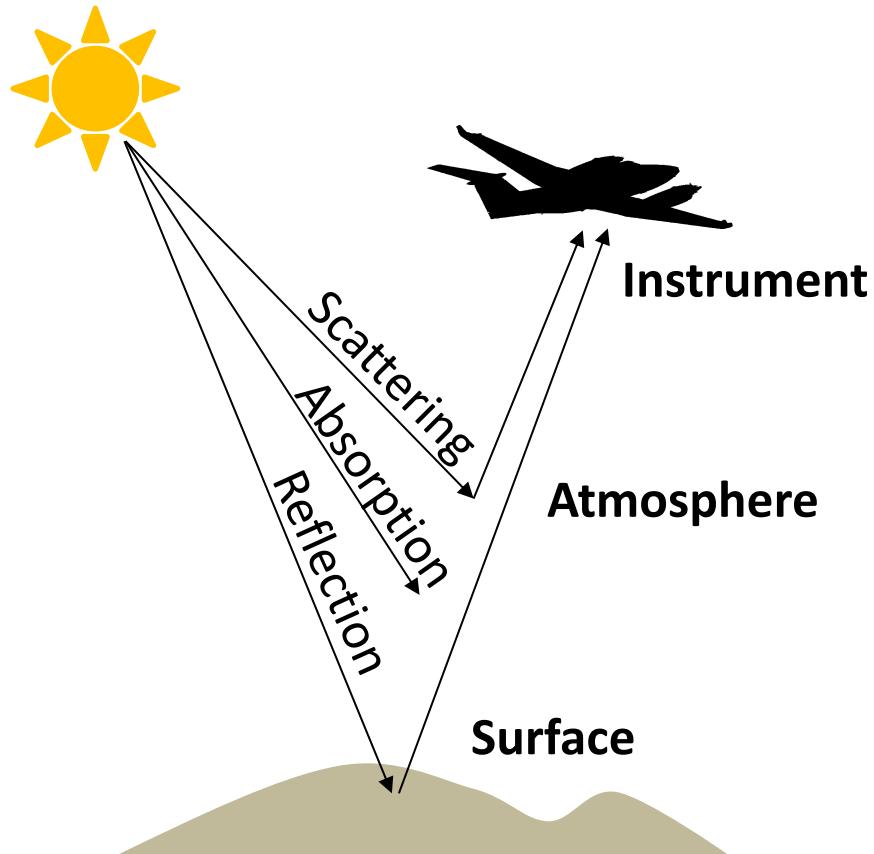


Dramatis Personae

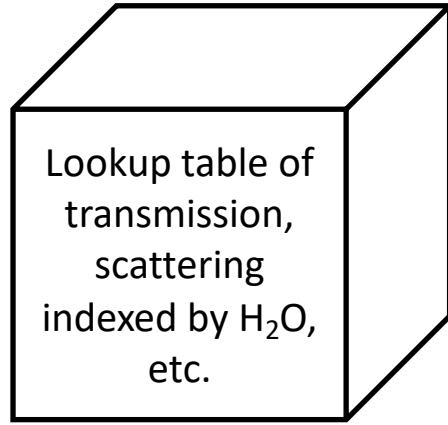


From radiance to reflectance

[Thompson et al., *Remote Sensing of Environment* 2015, 2018, 2019a, 2019b]

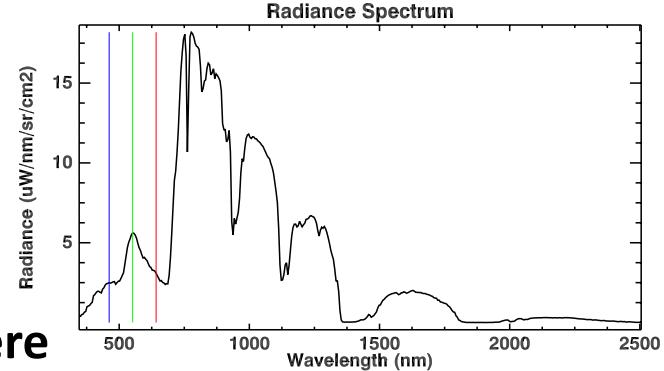


Conventional atmospheric correction: A sequential process



1. In advance, do RTM calculations

2. Estimate atmosphere
(typically by band ratios)

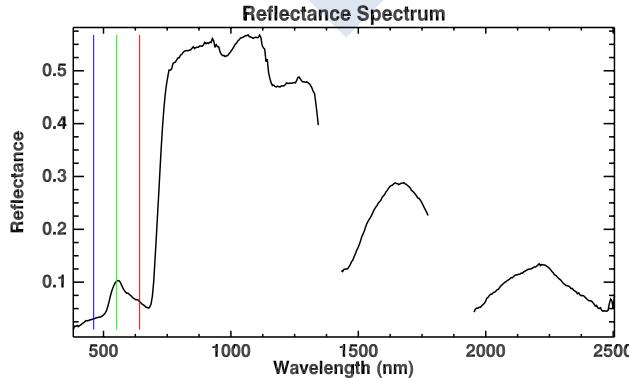


3. Algebraic
Inversion

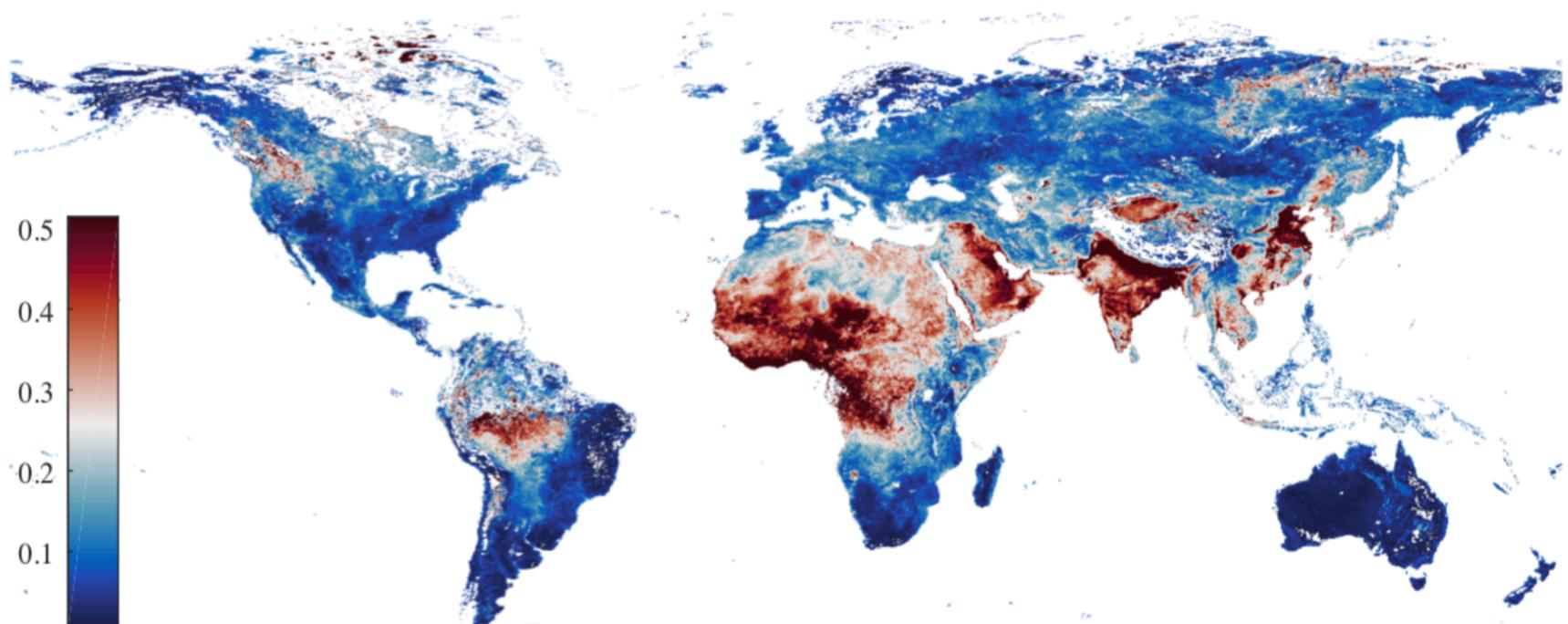
measurement

$$\rho_{obs}^* = \rho_a + \frac{T\rho_s}{1 - S\rho_s}$$

reflectance



Global spectroscopy missions are an atmospheric correction challenge

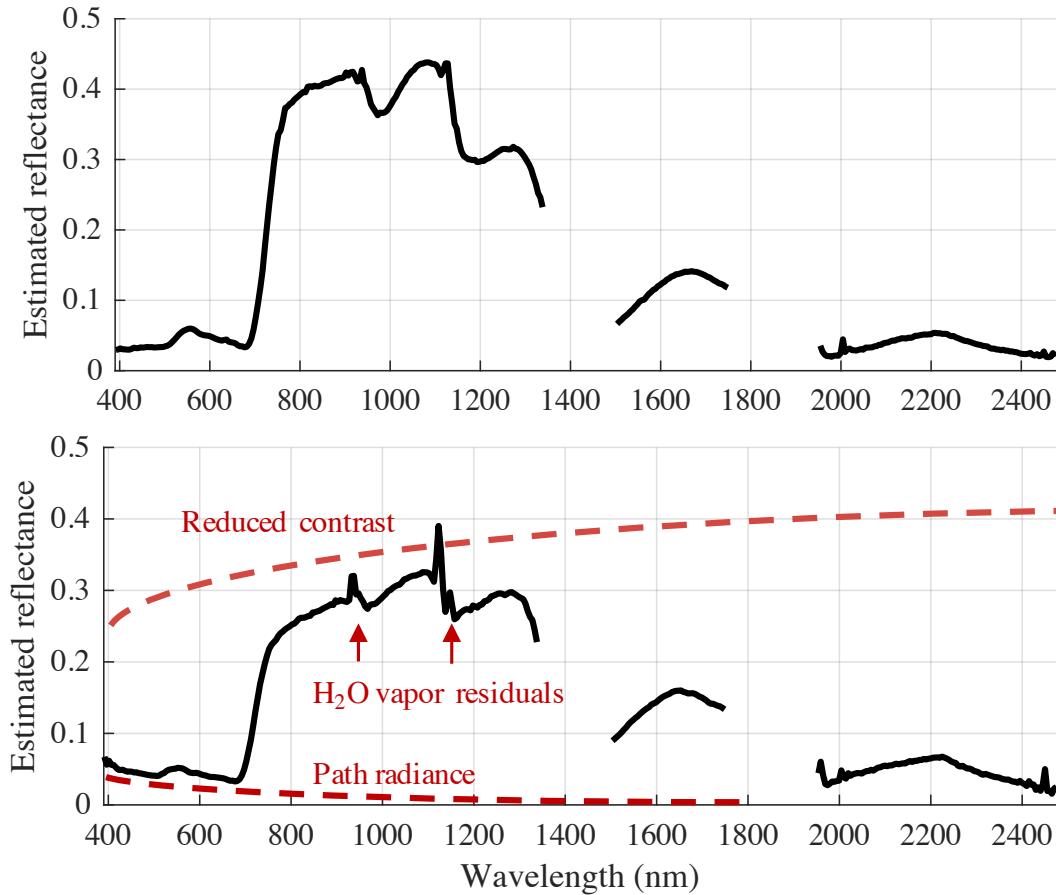


Annual average AOD

Thompson et al., (in review)



Global spectroscopy missions are an atmospheric correction challenge



Optimal Estimation Theory [Rodgers 2000]: Simultaneous estimation of surface and atmosphere

- **A true spectroscopic retrieval** that can exploit information distributed across the spectrum, helping to disentangle surface and atmosphere
- **A rigorous probabilistic formulation** incorporates prior knowledge via Bayes' rule
- **Comprehensive uncertainty estimates** can inform downstream analyses and global maps
- **Flexible state vectors** that might be more robust for difficult observing conditions
- **Elegant, conceptually simple 1-step estimation**

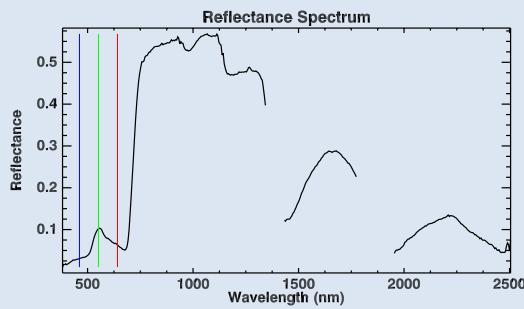


The “forward problem”

State vector

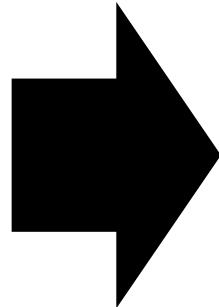
$$\mathbf{x} \in \mathbb{R}^N$$

$$\mathbf{x} = \begin{bmatrix} \text{Surface parameters} \\ \dots \\ \text{Atmosphere parameters} \\ \dots \\ \text{Instrument parameters} \\ \dots \end{bmatrix}$$



Forward model

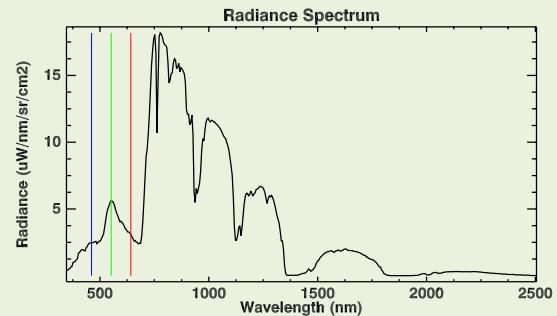
$$F(\mathbf{x}) : \mathbb{R}^N \mapsto \mathbb{R}^M$$



Measurement

$$\mathbf{y} \in \mathbb{R}^M$$

$$\mathbf{y} = \begin{bmatrix} \text{Calibrated at-aperture} \\ \text{radiance measurements} \end{bmatrix}$$

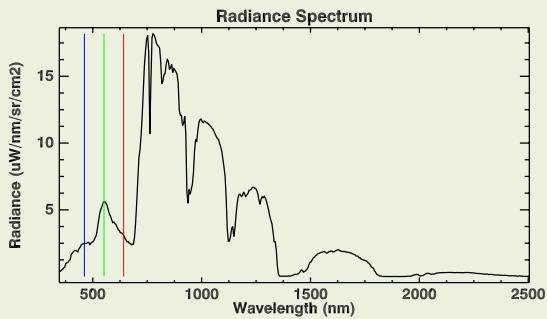


The “inverse problem”

Measurement

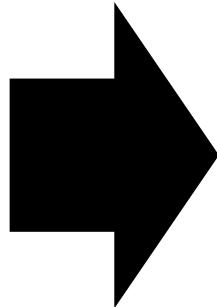
$$\mathbf{y} \in \mathbb{R}^M$$

$$\mathbf{y} = \begin{bmatrix} \text{Calibrated at-aperture} \\ \text{radiance measurements} \end{bmatrix}$$



Inversion algorithm

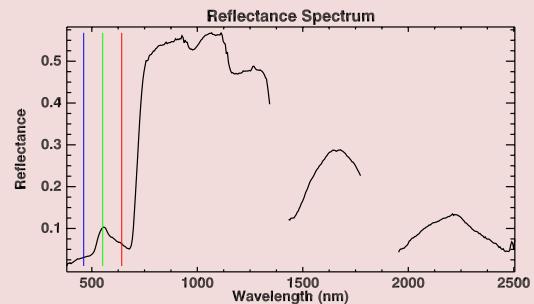
$$R(\mathbf{y}) : \mathbb{R}^M \mapsto \mathbb{R}^N$$



Estimated state vector

$$\hat{\mathbf{x}} \in \mathbb{R}^N$$

$$\hat{\mathbf{x}} = \begin{bmatrix} \text{Estimated surface parameters} \\ \dots \\ \text{Estimated atmosphere parameters} \\ \dots \\ \text{Estimated instrument parameters} \\ \dots \end{bmatrix}$$



Maximum *A Posteriori* solution

$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{y})}$$

Maximum *A Posteriori* solution

$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{y})}$$

The *Maximum A Posteriori* estimation is equivalent to the optimization:

$$\chi^2(\mathbf{x}) = (\mathbf{F}(\mathbf{x}) - \mathbf{y})^T \mathbf{S}_\epsilon^{-1} (\mathbf{F}(\mathbf{x}) - \mathbf{y}) + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)$$

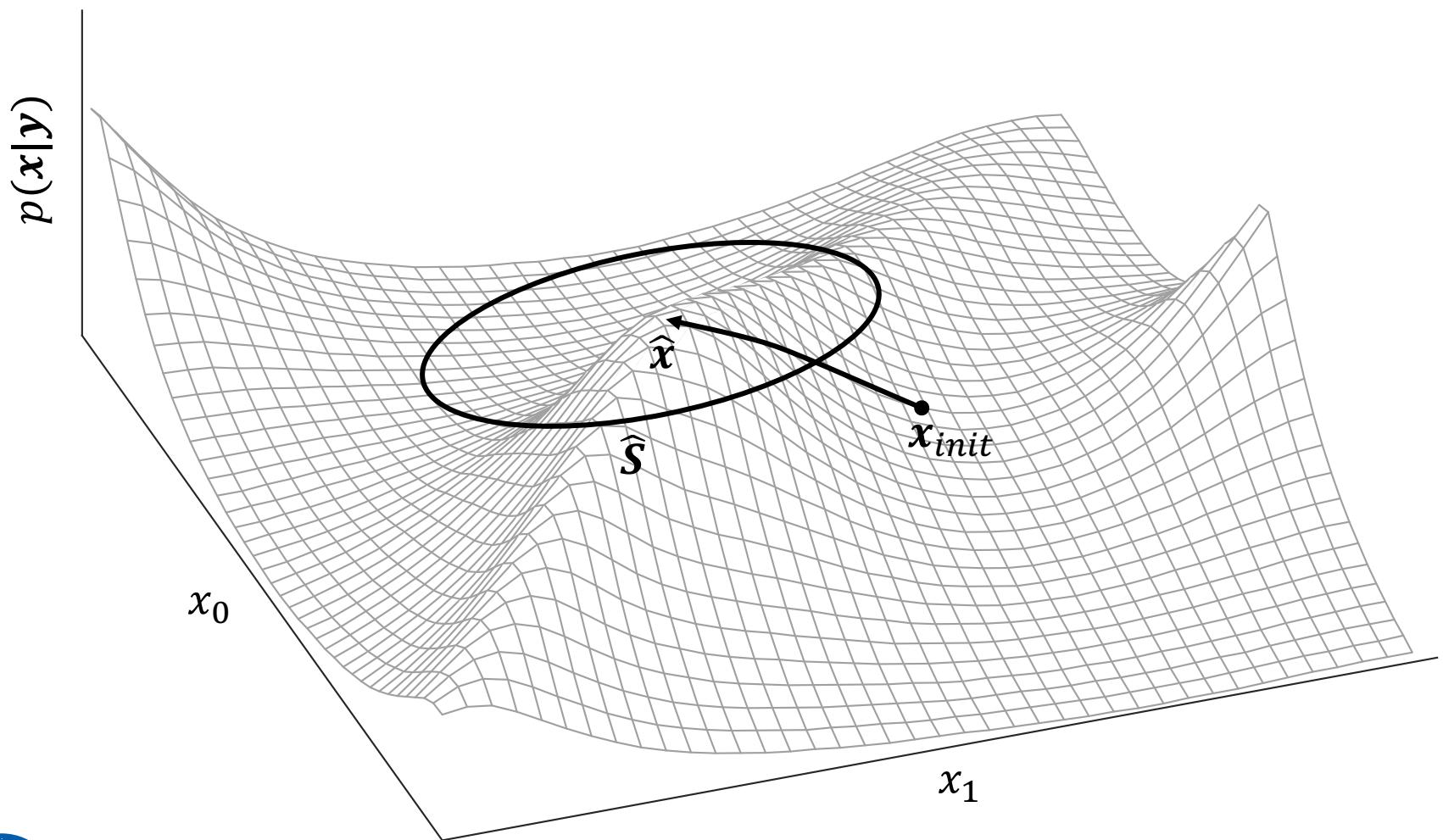
 Cost

 Model match to measurement

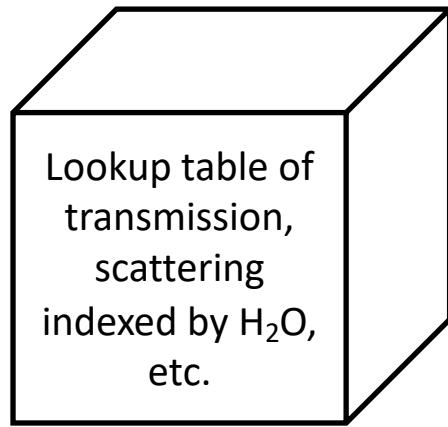
 Bayesian prior

... we can solve it by conjugate gradient descent.

Maximum A Posteriori estimation

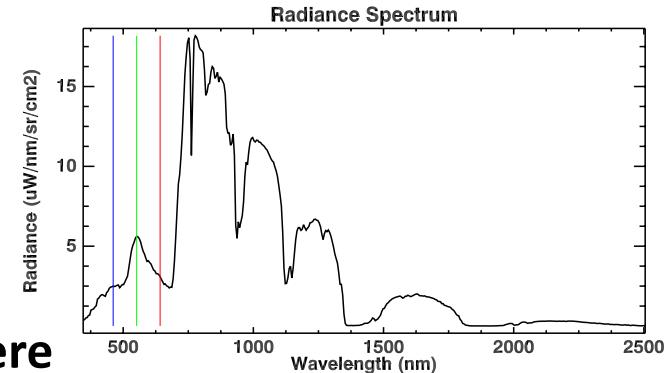


Conventional atmospheric correction: A sequential process



1. In advance, do
RTM calculations

2. Estimate atmosphere
(typically by band ratios)

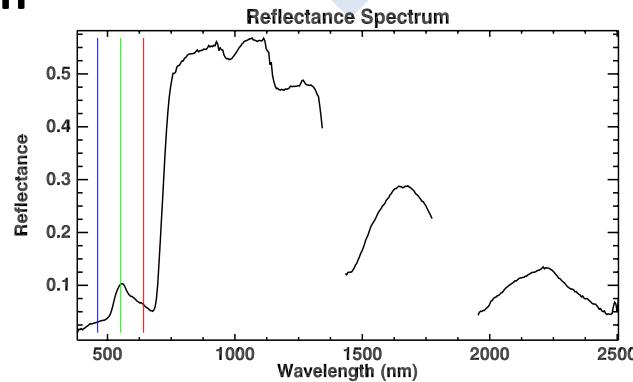


measurement

reflectance

$$\rho_{obs}^* = \rho_a + \frac{T\rho_s}{1 - S\rho_s}$$

3. Algebraic
Inversion



david.r.thompson@jpl.nasa.gov

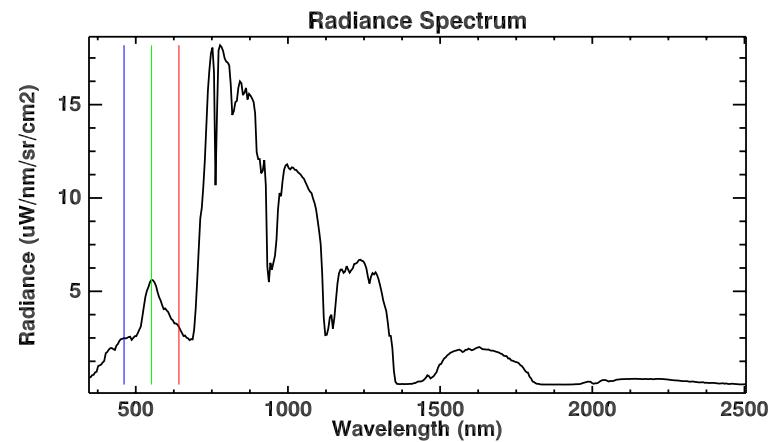
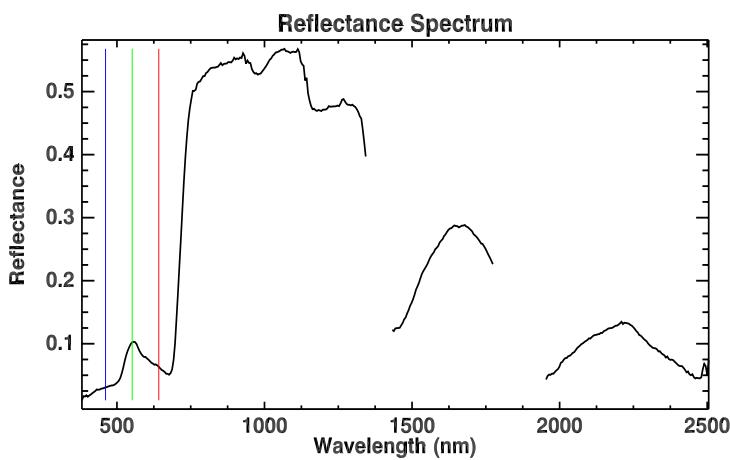
3/10/21



Iterative simultaneous estimation of atmosphere and surface

1. Predict
radiance

$$y = F(x) + \epsilon$$



2. Optimize
state vector

$$\chi^2(x) = \underbrace{(F(x) - y)^T S_\epsilon^{-1} (F(x) - y)}_{\text{Cost}} + \underbrace{(x - x_a)^T S_a^{-1} (x - x_a)}_{\text{Model match to measurement}} + \underbrace{(x - x_a)^T S_a^{-1} (x - x_a)}_{\text{Bayesian prior}}$$



Variability due to measurement noise vs. unknown state parameters

Total observation noise

$$\mathbf{S}_\epsilon = \mathbf{S}_y + \mathbf{K}_b \mathbf{S}_b \mathbf{K}_b^T$$

Measurement noise
(instrument effects)

- Photon noise
- Read noise
- Dark current noise

Jacobian WRT unknowns

$$\mathbf{S}_\epsilon = \mathbf{S}_y + \mathbf{K}_b \mathbf{S}_b \mathbf{K}_b^T$$

Unknown parameters in the
observation system

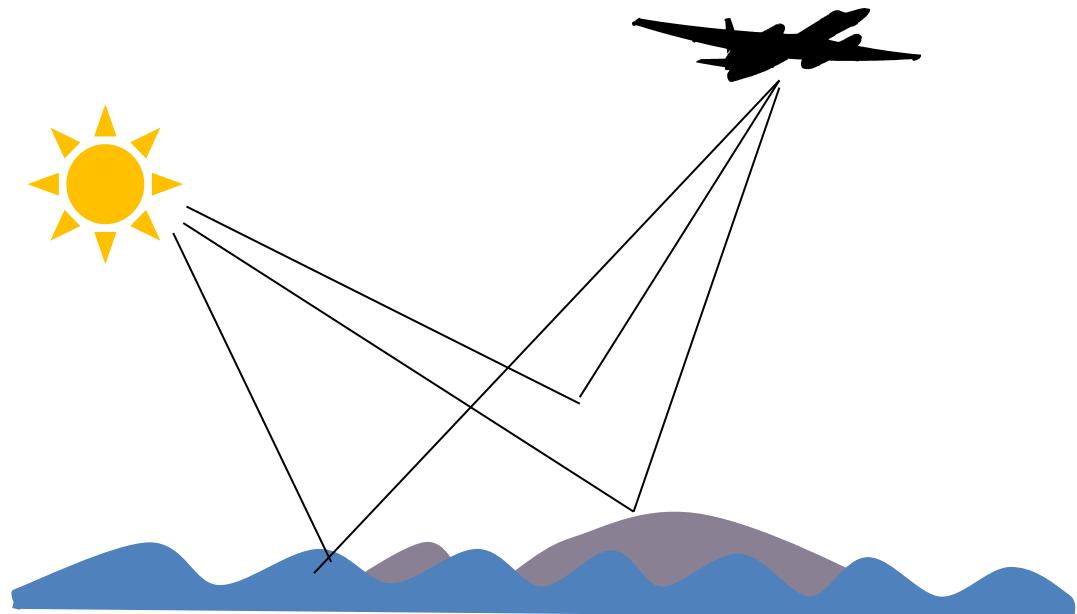
- Sky view factor
- H₂O absorption coefficient intensity
- Systematic radiative transfer error
- Uncorrelated radiative transfer error

Agenda

Algorithms

Case Studies

Science & Future Missions



California Study

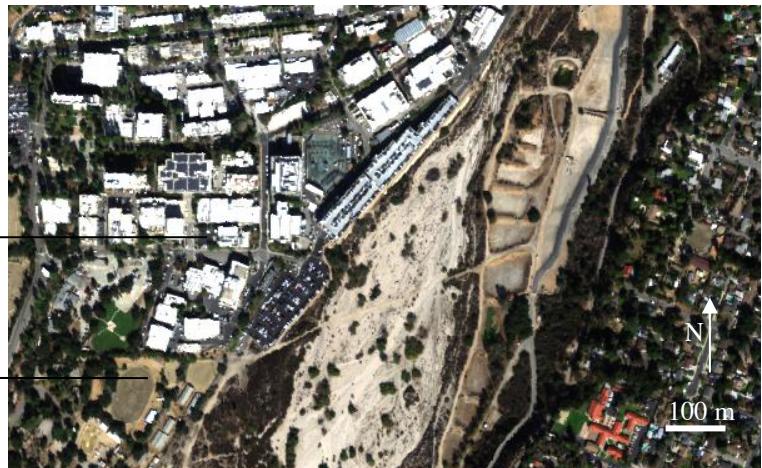
[Thompson et al., *Remote Sensing of Environment*, 2018]

- In-situ AOD via Reagan sunphotometers
- In-situ surface reflectance via ASD Fieldspec

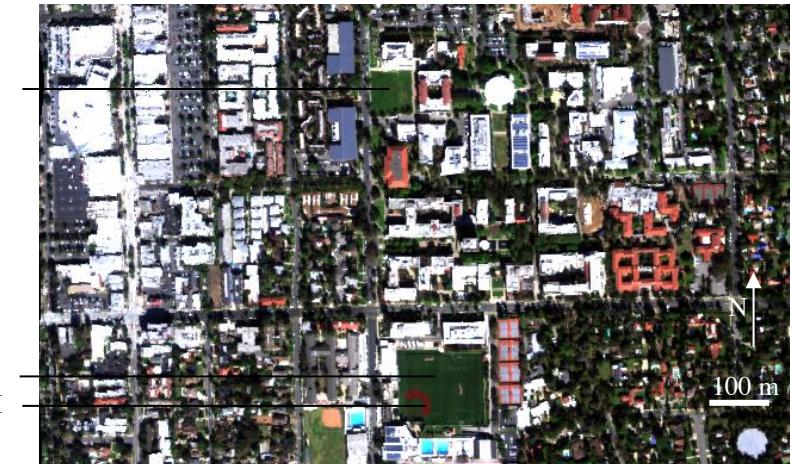
Ivanpah Playa



Jet Propulsion Laboratory



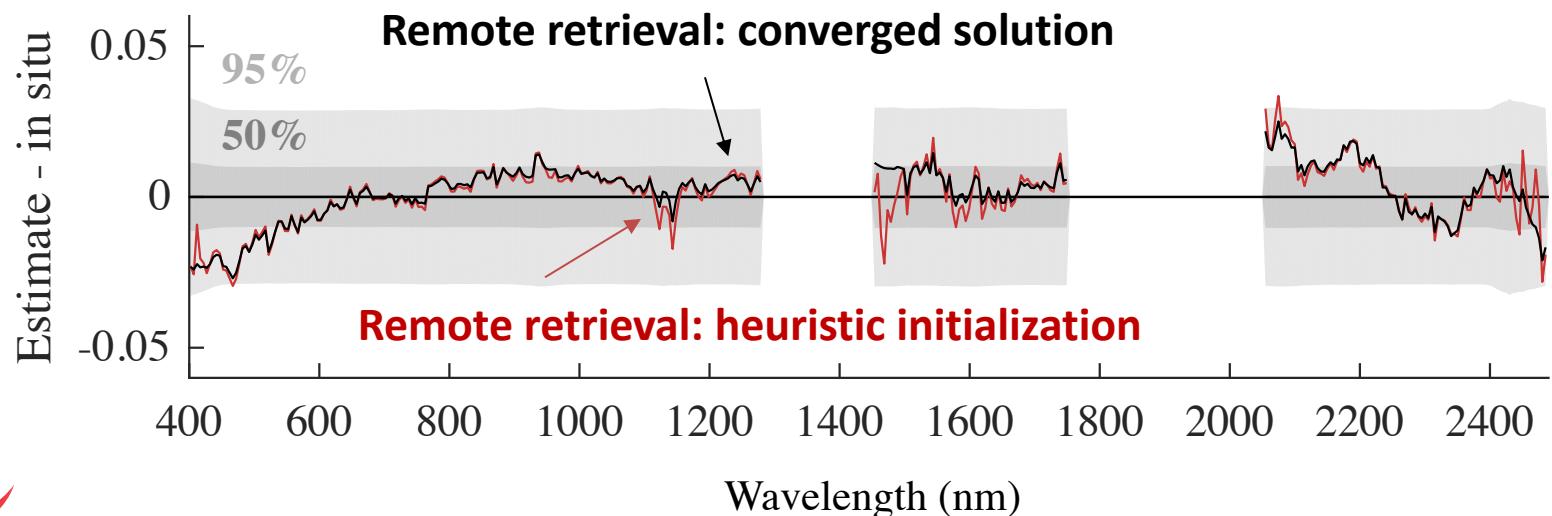
California Institute of Technology

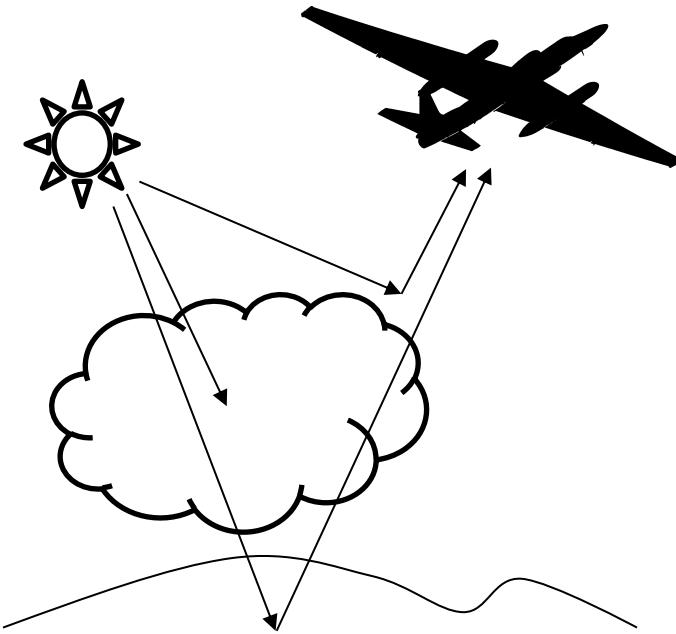


From Thompson et al., RSE 2018.

Posterior uncertainty compared to actual discrepancies

[Thompson et al., *Remote Sensing of Environment* 2018]





Model components

Pre-defined
Statistical, fit to data
Retrieved in the inversion

Instrument: AVIRIS-NG

- Instrument model with Wavelength- and signal-dependent SNR
- Photon shot & read noise
- Uncorrelated calibration uncertainty
- Systematic calibration / RT uncertainty

Atmosphere: MODTRAN 6.0 RTM

- DISORT MS, Correlated-k
- Rural aerosol model
- broad prior uncertainties
- Unmodeled unknowns, including H_2O absorption coefficients
- H_2O , AOD retrieved

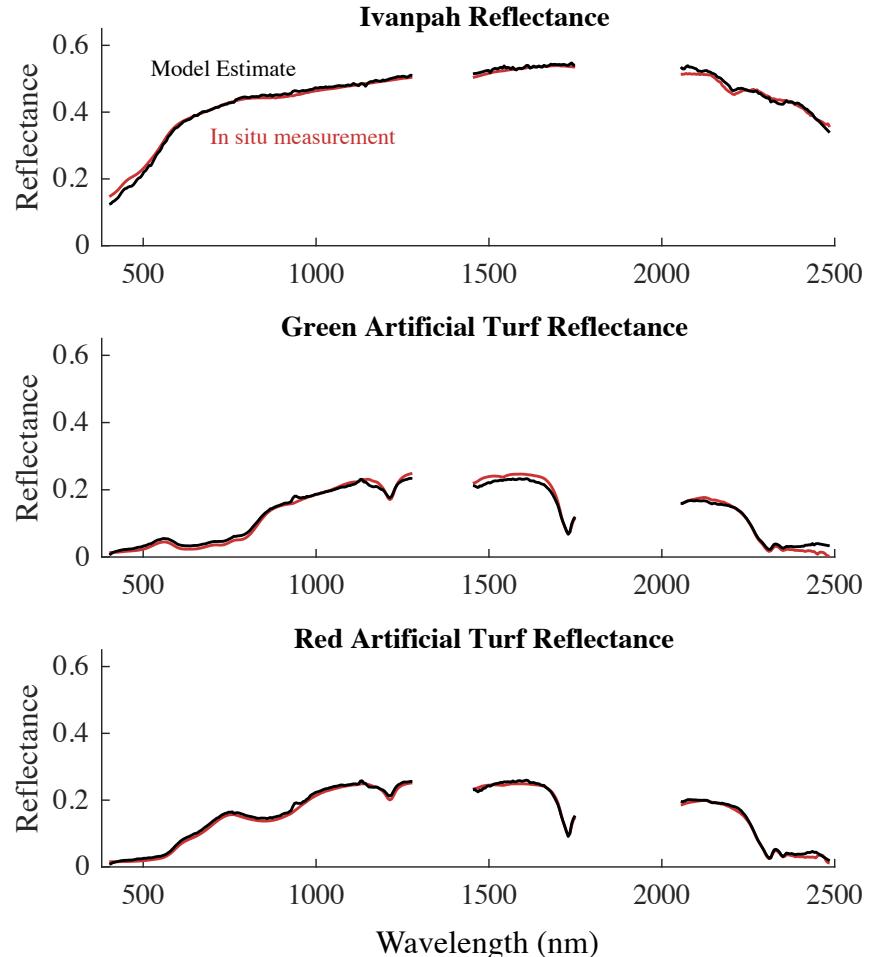
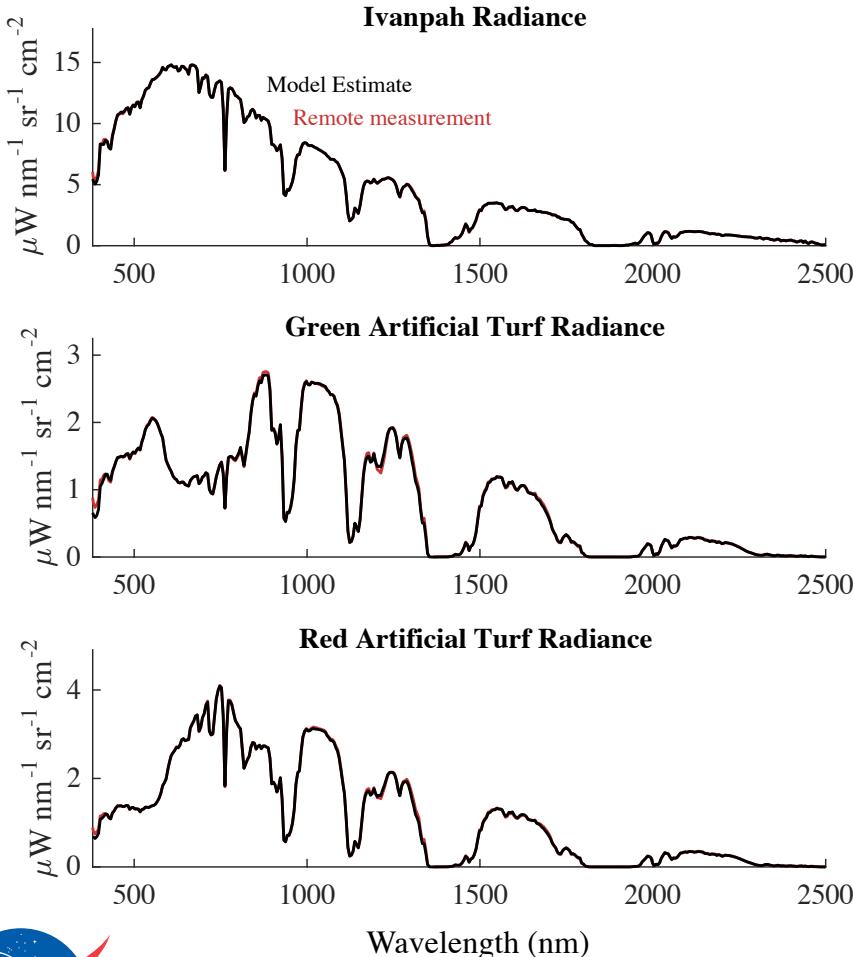
Surface: Multi-component Multivariate Gaussians

- Prior based on universal library, highly regularized to permit accurate retrieval of arbitrary shapes
- Reflectance estimated independently in every channel



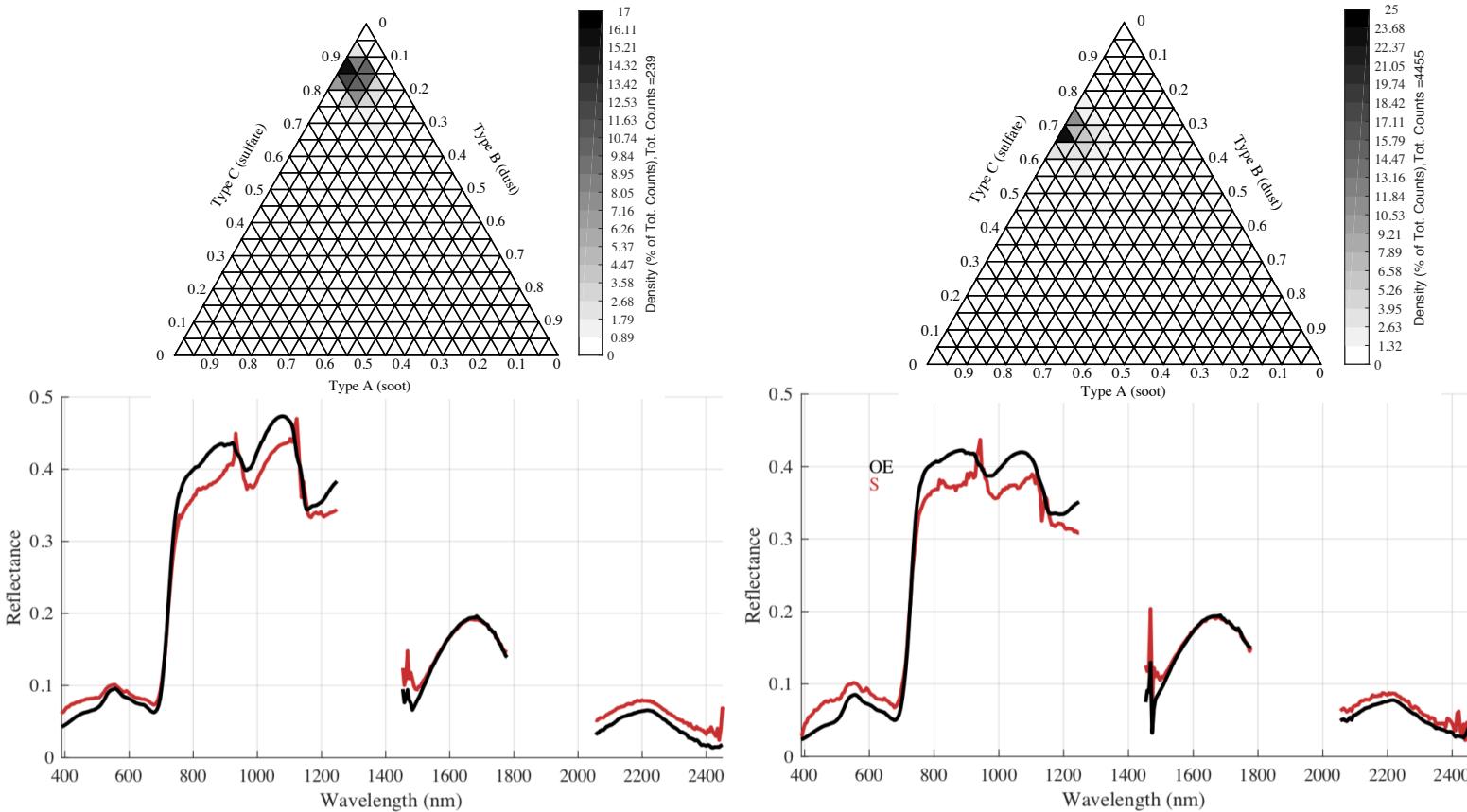
Reflectance estimate vs. in situ

[Thompson et al., *Remote Sensing of Environment* 2018]



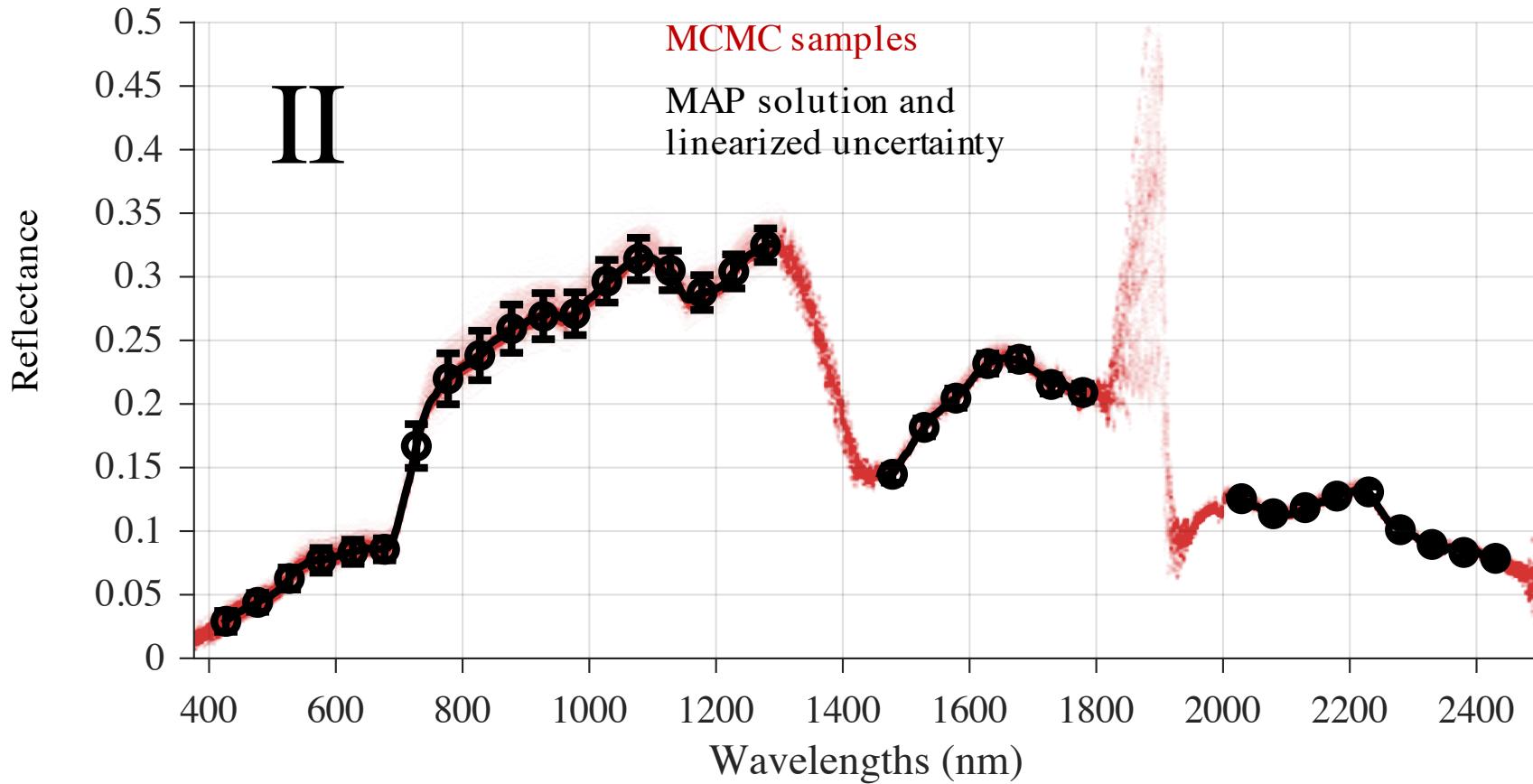
High aerosol loads in an India-wide campaign

Thompson et al., *Remote Sensing of Environment* 2019a (in press)



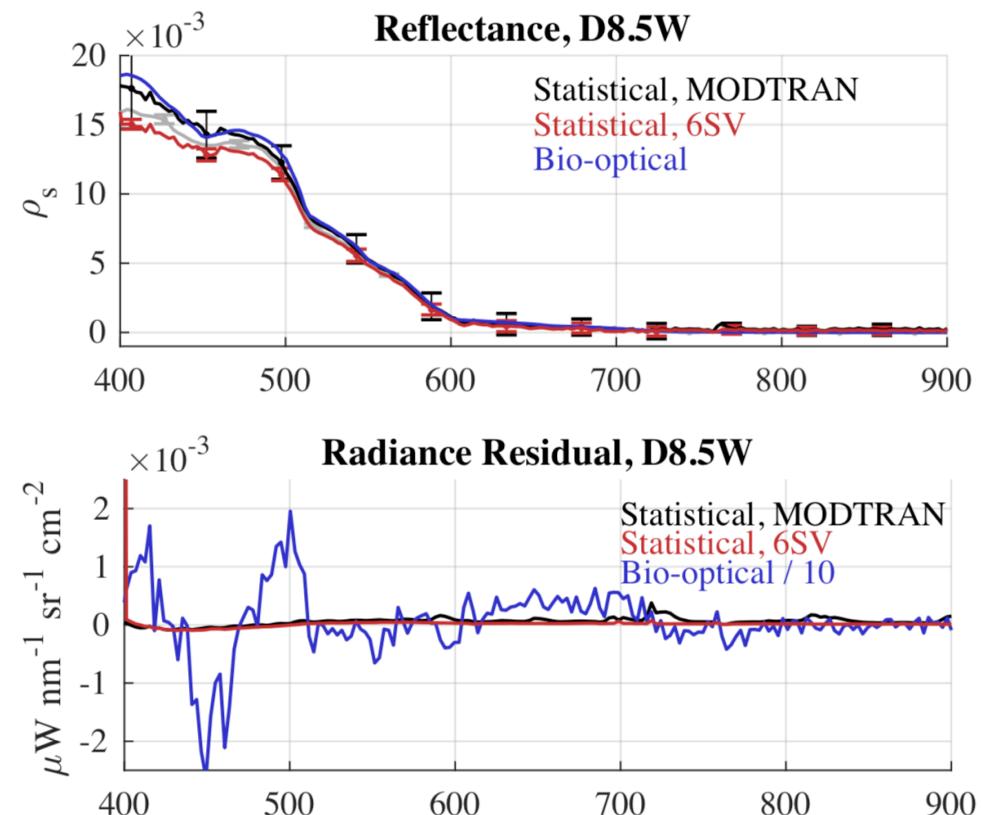
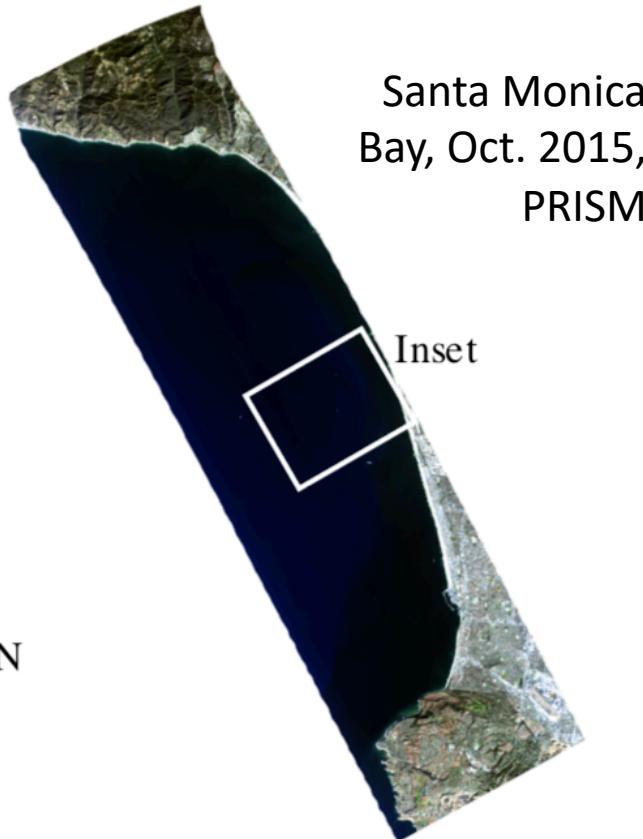
Maximum A Posteriori vs. MCMC

Thompson et al., Remote Sensing of Environment 2019a (in press)



Application to coastal and inland waters

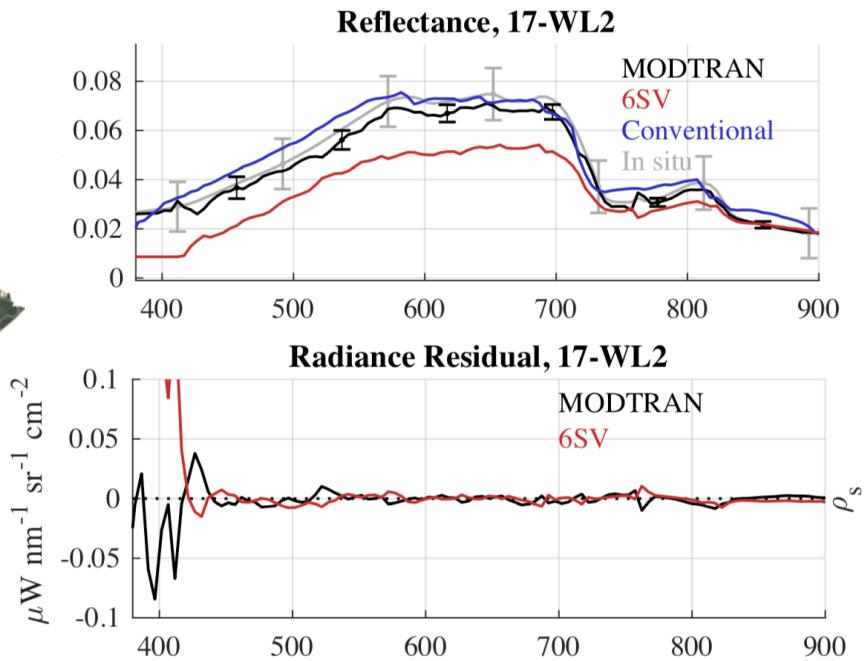
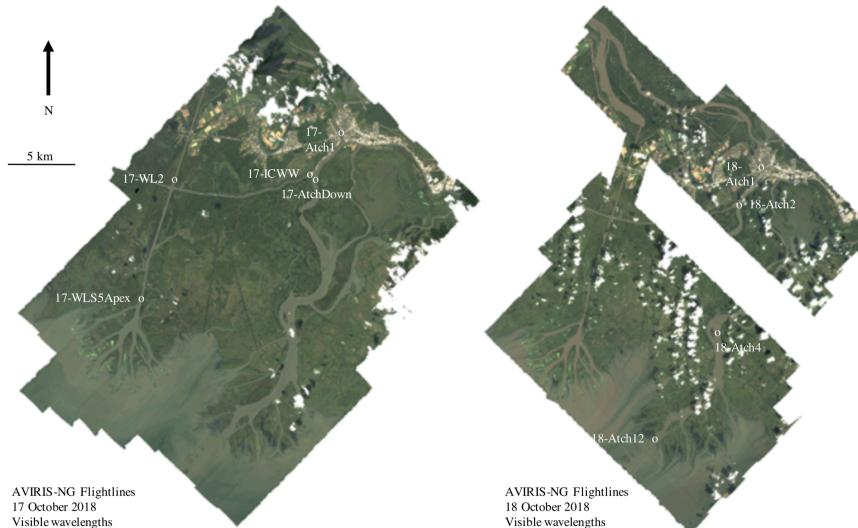
Thompson et al., RSE 2019b (in press)



Application to coastal and inland waters

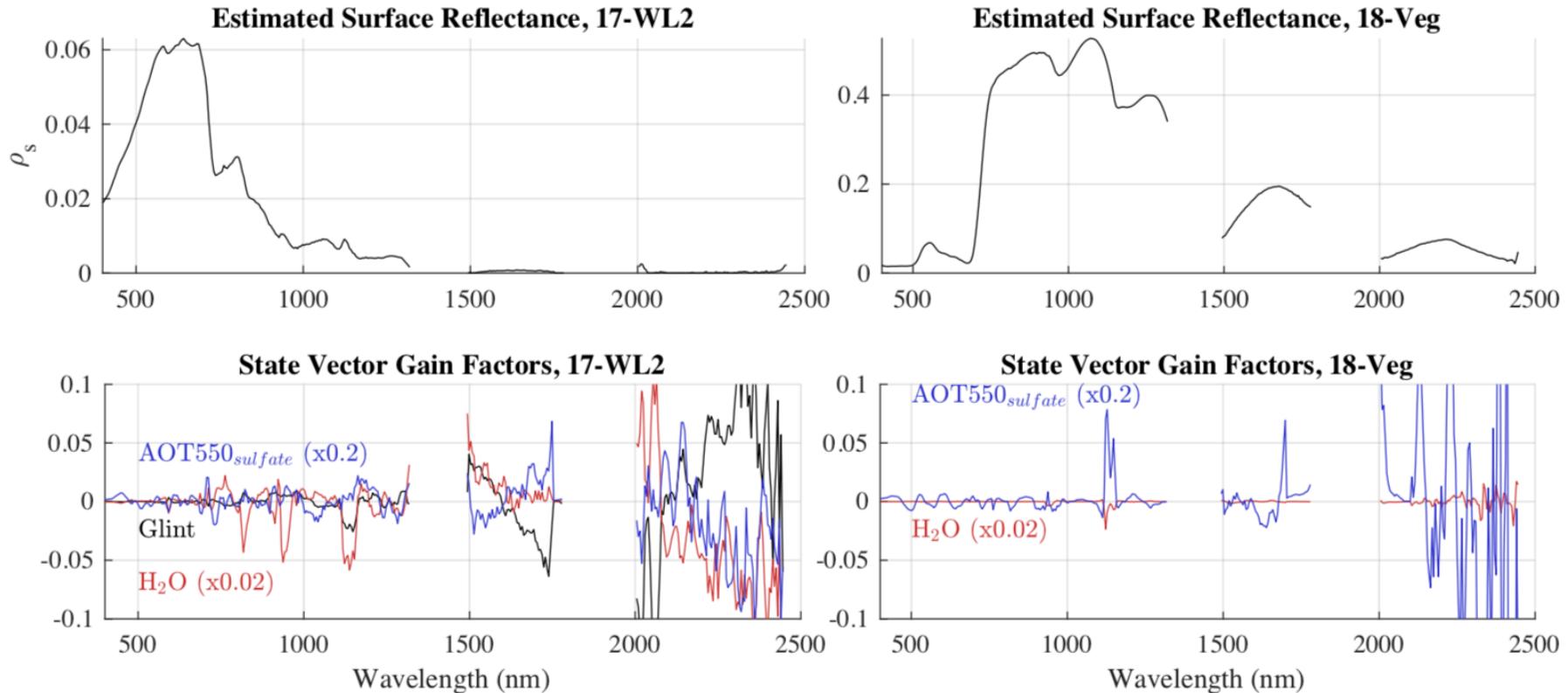
Thompson et al., RSE 2019b (in press)

Lower Louisiana & Achafalaya River Delta, AVIRIS-NG 2016



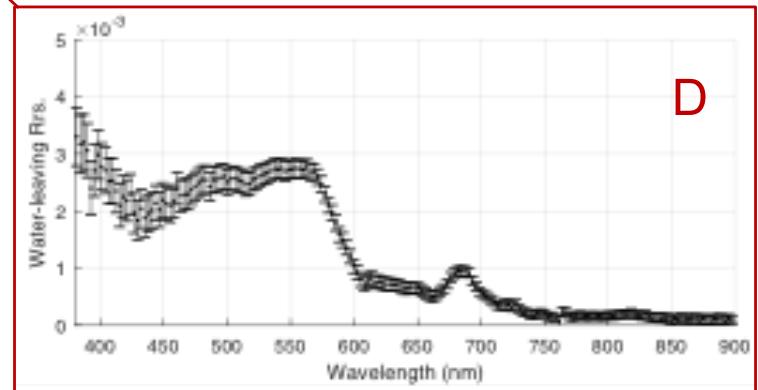
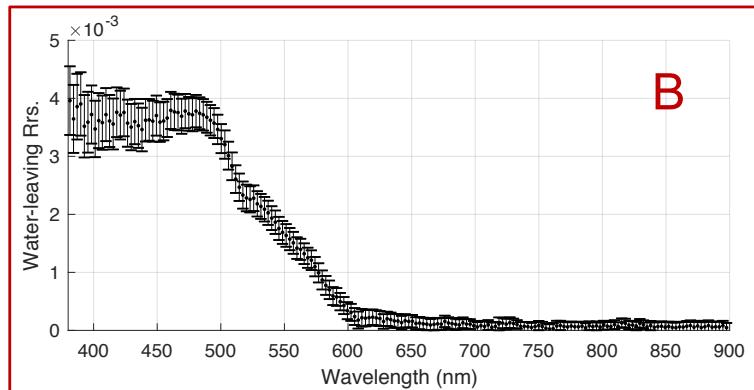
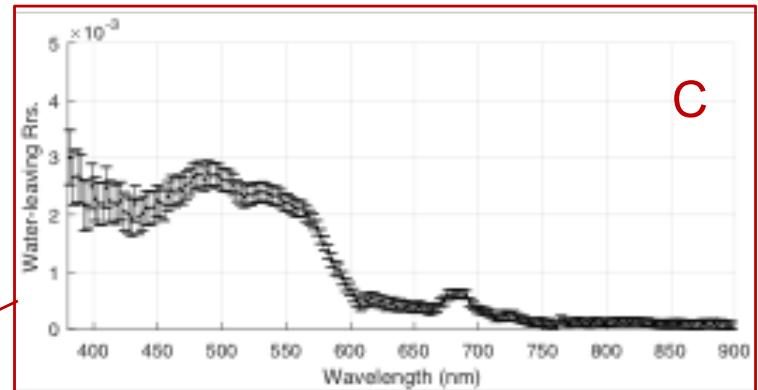
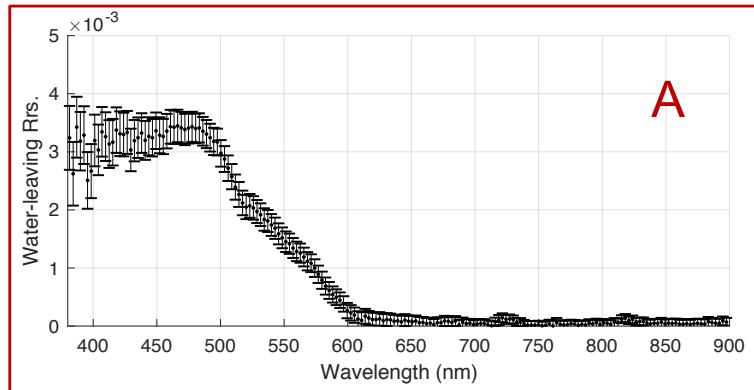
Different surfaces provide varying atmospheric information

Thompson et al., RSE 2019b (in press)



Uncertainty quantification and propagation

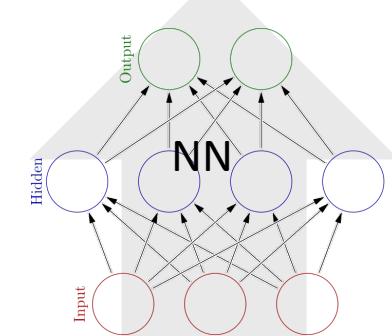
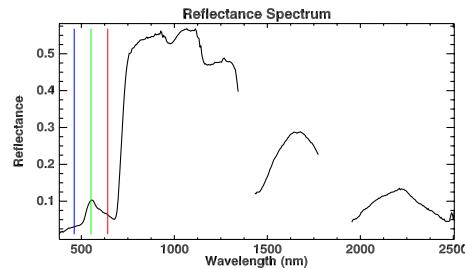
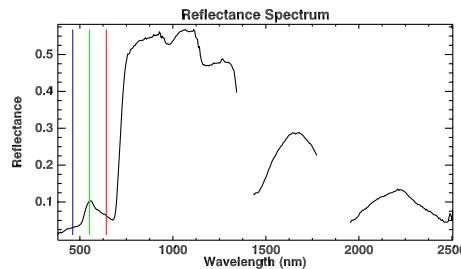
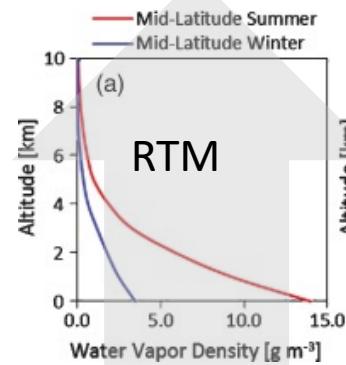
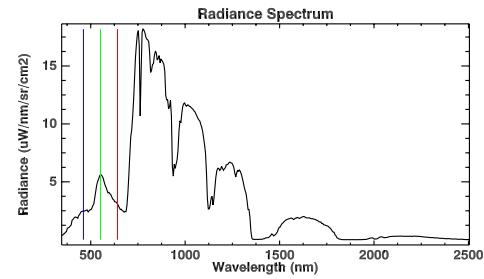
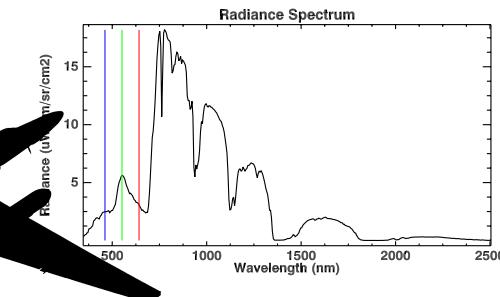
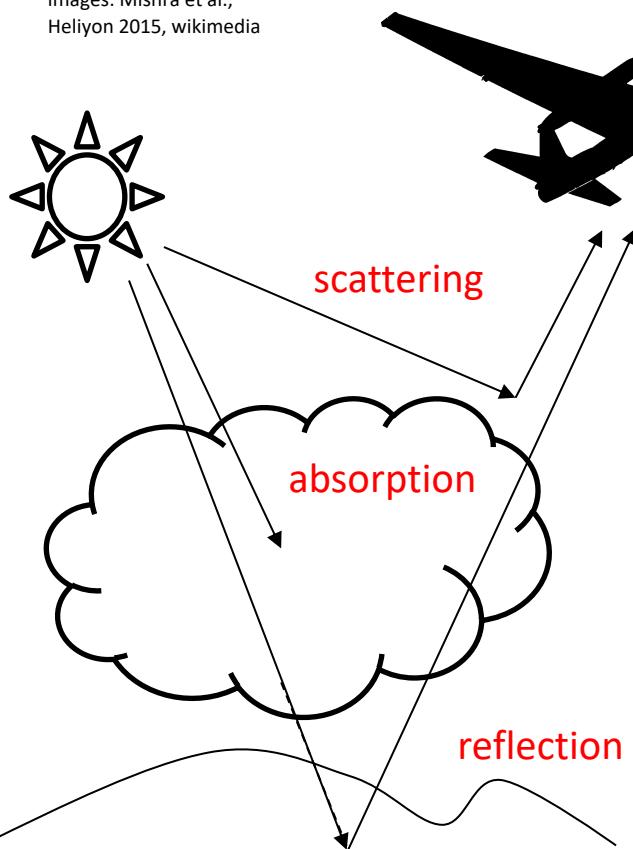
Frouin et al., Frontiers in Marine Science, 2019 (in press)



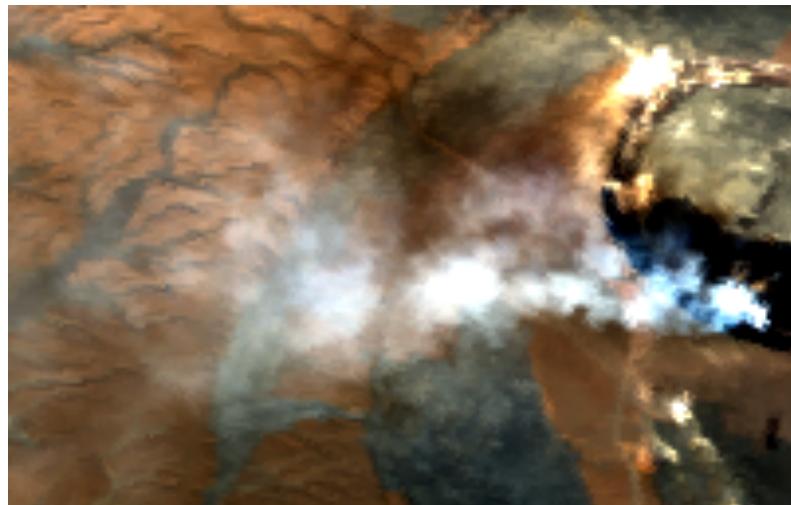
Speeding up the forward model

Bue et al., Atmospheric Measurement Techniques, 2019

images: Mishra et al.,
Heliyon 2015, wikipedia

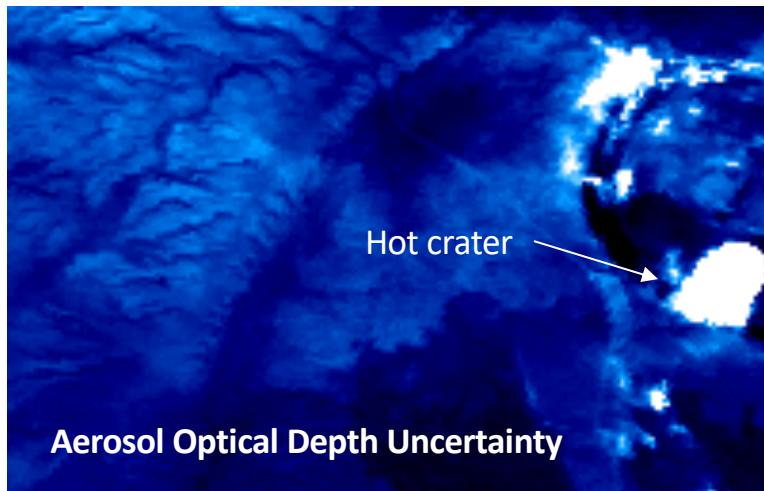
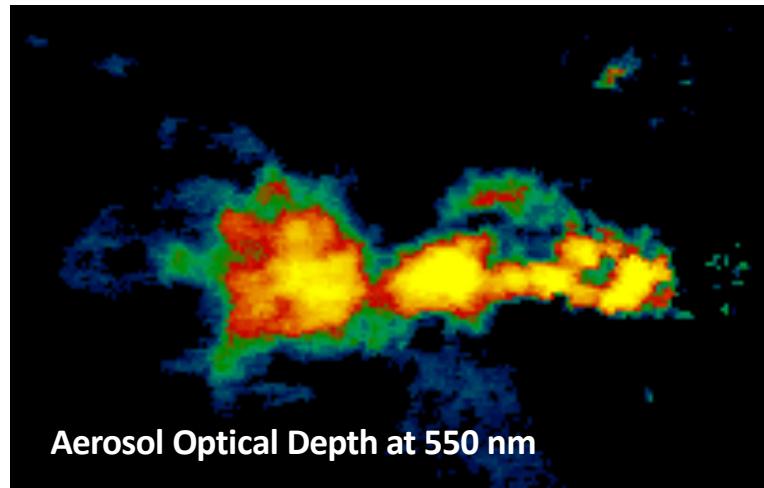


Aerosol mapping examples (Hawaii campaign)



AVIRIS-C f170127t01p00r16
(subset, visible bands)

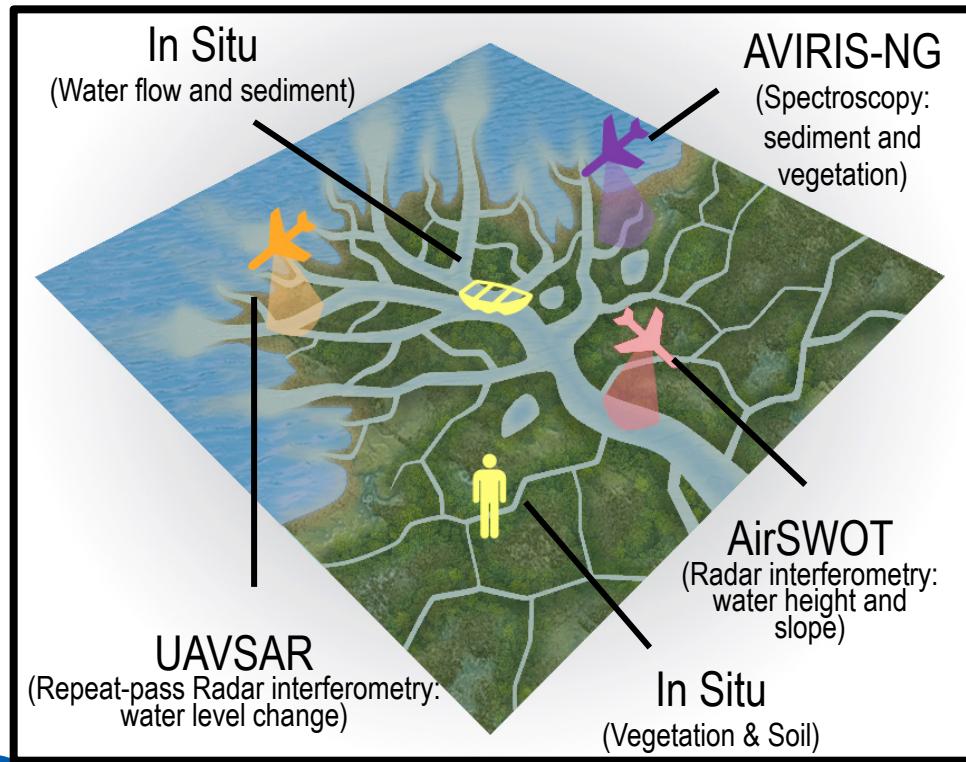
Combined estimate of H_2O vapor, AOT,
surface reflectance and temperature



Airborne (2019 – 2024): Delta-X

PI: Marc Simard (JPL)

Urgency: If ignored, Relative Sea Level Rise (RSLR) will very soon have devastating consequences on the livelihood of the half billion people that live in these low-lying coastal regions. Nearly all the world's major river deltas are threatened along with the services they provide: flood protection, carbon sequestration, biodiversity and food supply.



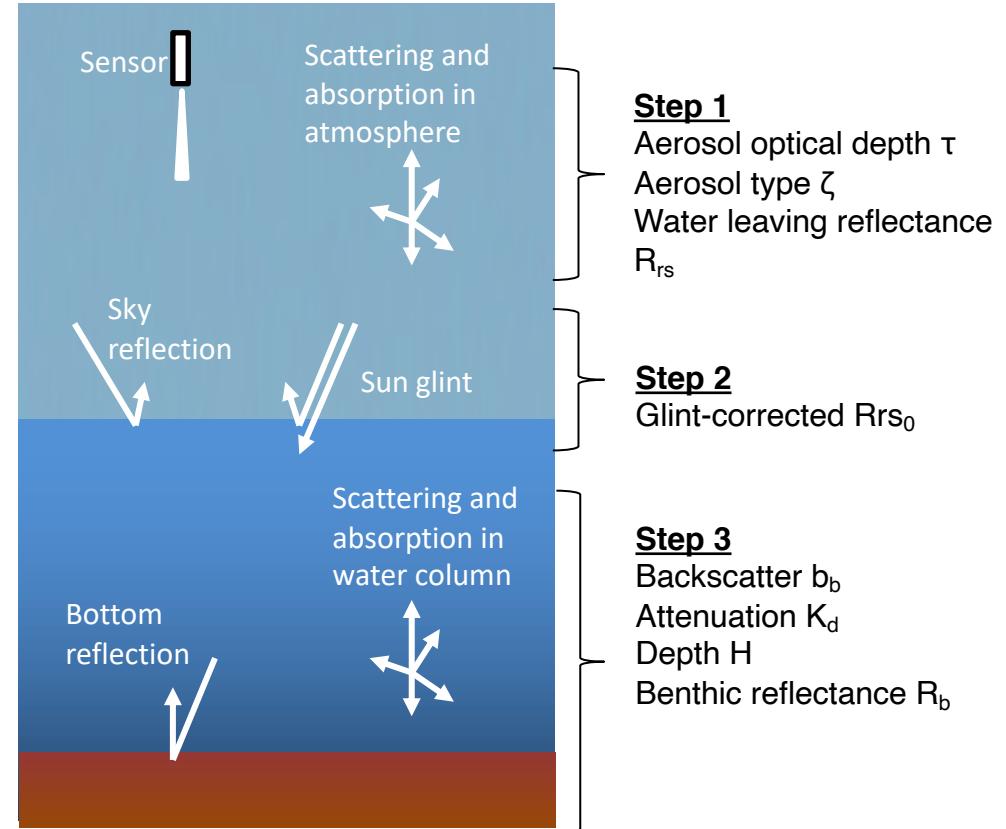
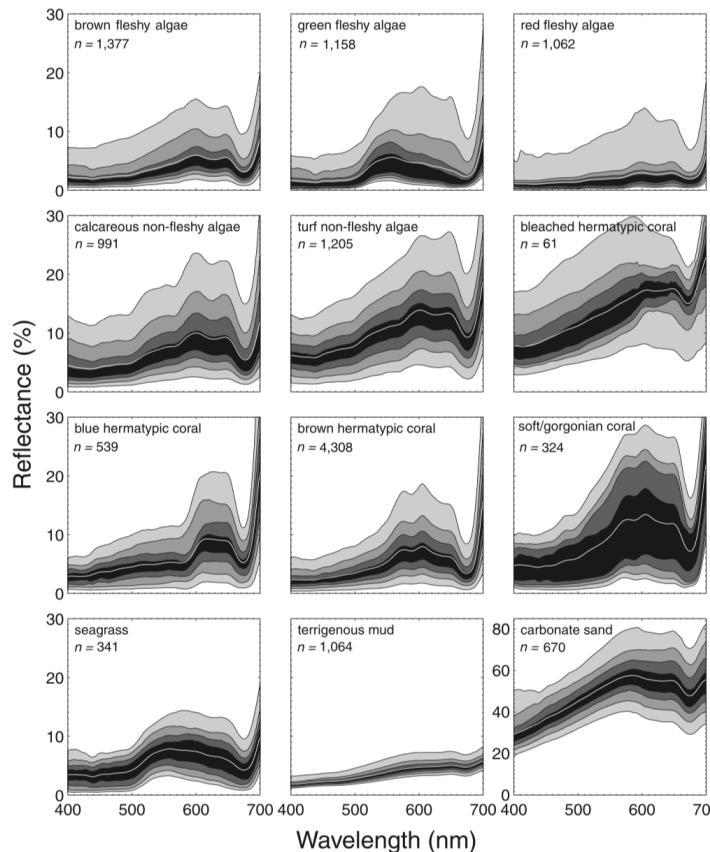
Delta-X Science Question: Will river deltas completely drown, or some parts of these deltas accumulate sufficient sediments and produce enough plants to keep pace with RSLR ?



Airborne (2016 – 2019): CORAL

PI: Eric Hochberg (BIOS)

Deputy PI: Michelle Gierach (JPL)



Hochberg et al., *Remote Sensing of Environment* 2003



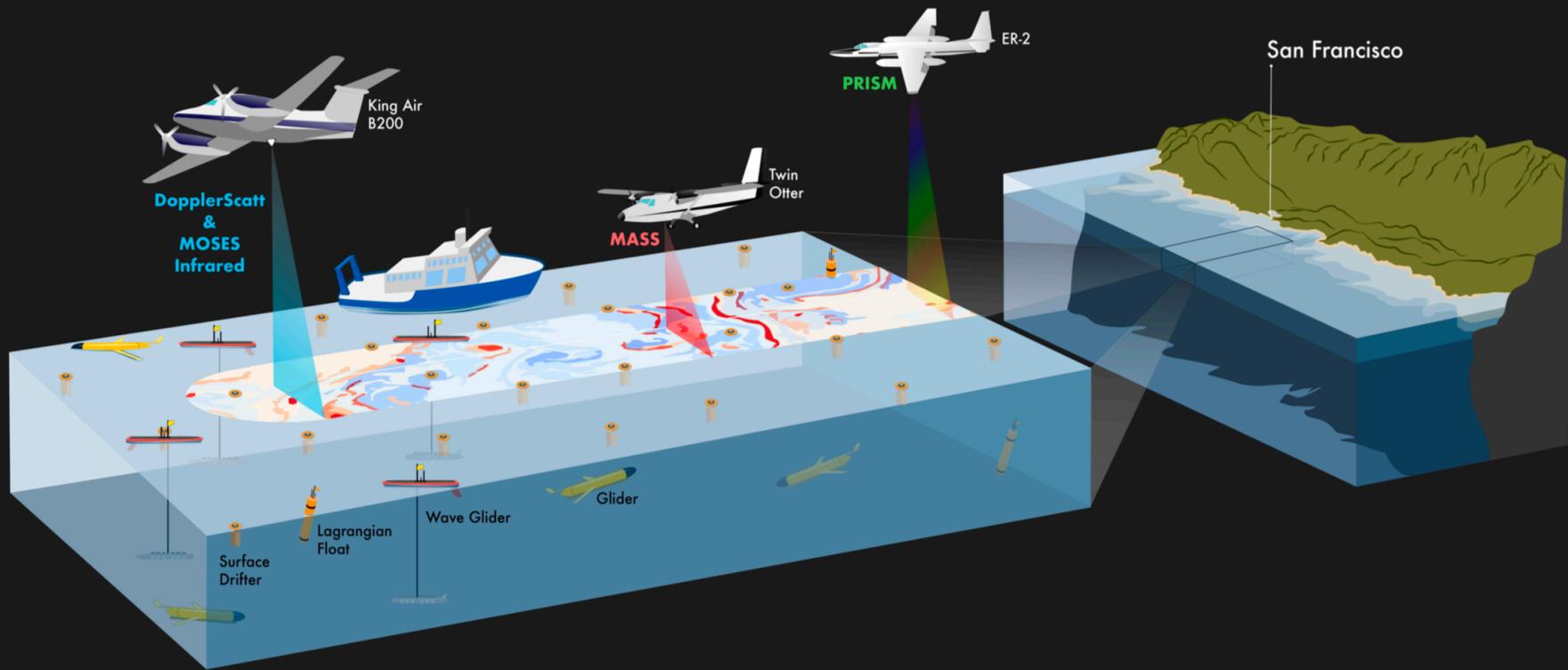
3/10/21

Thompson et al., *Remote Sensing of Environment* 2017

david.r.thompson@jpl.nasa.gov

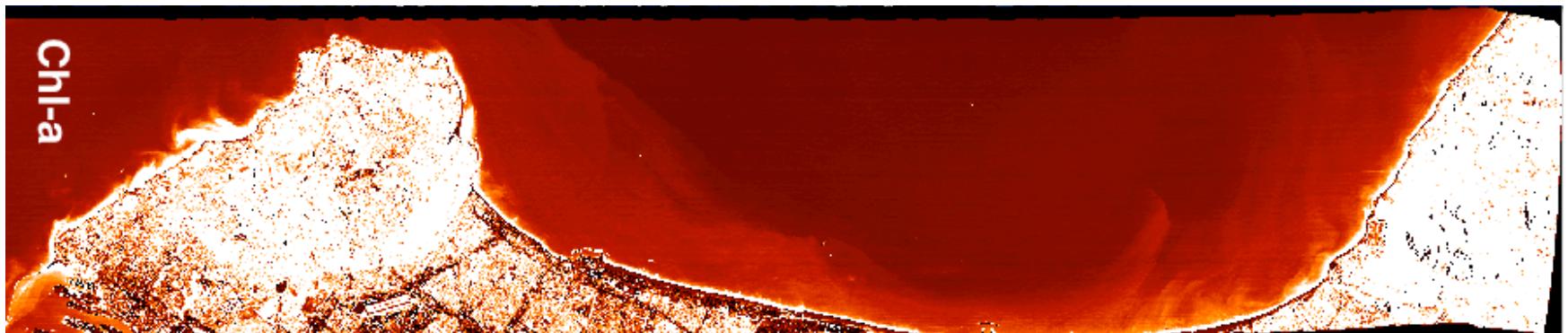
Airborne (2020 - 2024): S-MODE

PI: Tom Farrar, WHOI

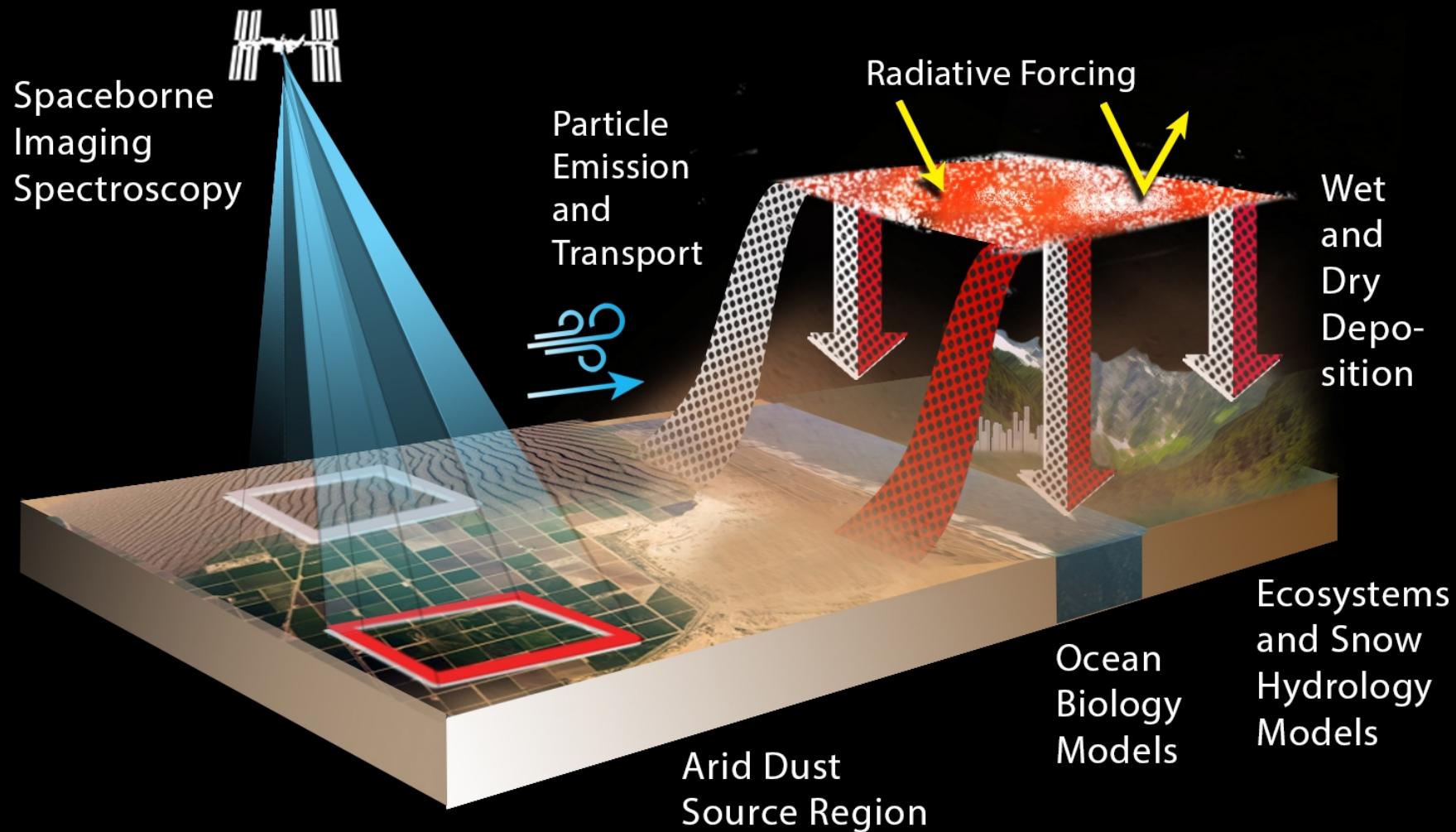


Airborne (2020 - 2024): S-MODE

PI: Tom Farrar, WHOI



Orbital (2021 – 2022): EMIT



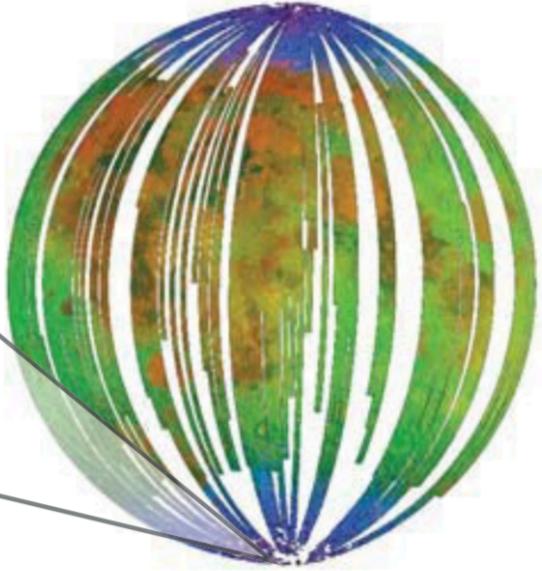
Selected: Lunar Trailblazer

PI: Bethany
Ehlmann,
Caltech

Instrument
Scientist, HVM3:
David R.
Thompson, JPL

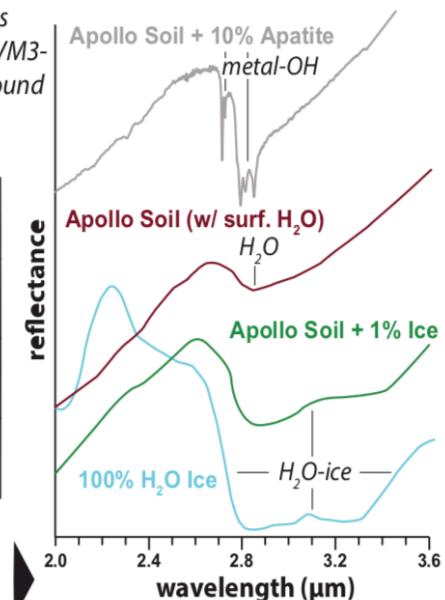
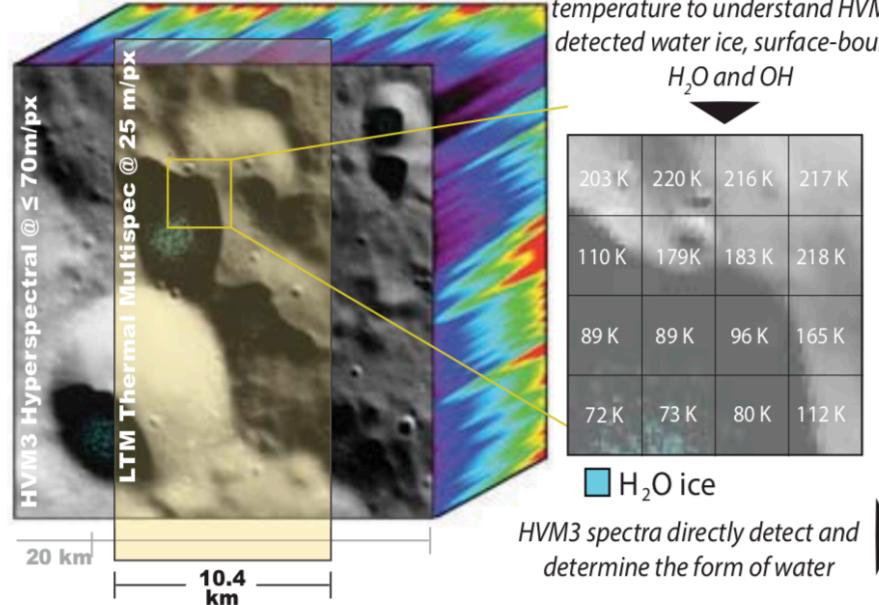
Faustini crater
PSR from
terrain-scattered light
(Cisneros et
al., 2016)

OH/H₂O
absorption
(blue) at 3- μ m
from M3
(Pieters et al.,
2009)



Standard Lunar Trailblazer Observation

1 HVM3 cube + 1 nested LTM cube



Global
VSWIR

Targeted
VSWIR

Targeted
VNIR

Other orbital investigations

Recommended
Decadal Survey
Investigation:
SBG (NASA)

2000 2005 2010 2015 2020 2025 2030

Hyperion (NASA Pathfinder)

CHRIS/PROBA (ESA)

HICO (ONR/NASA)

DESIS (DRL)

EMIT (NASA)

ENMAP (DRL)

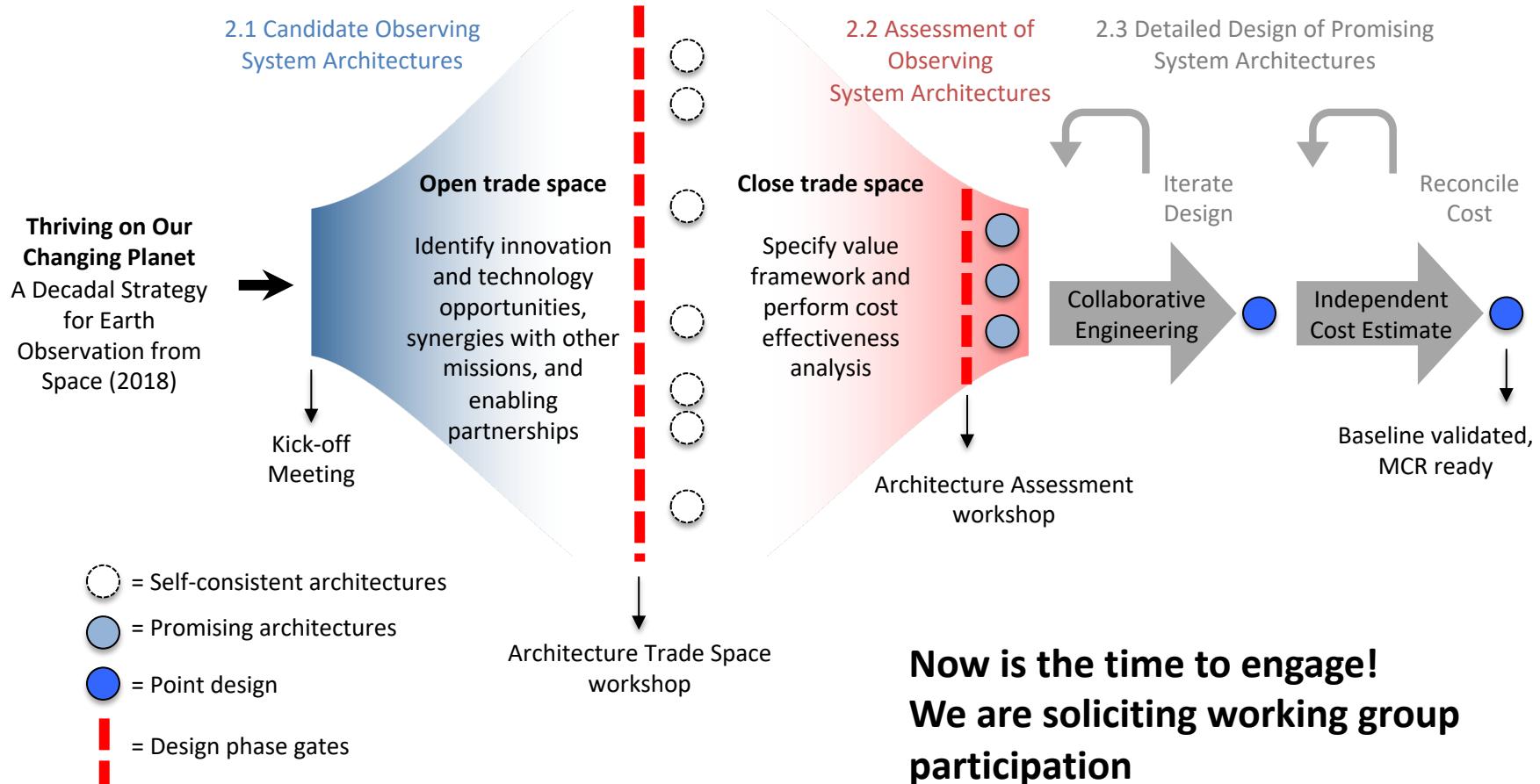
HISUI (Japan, METI)

AHSI (China)

PRISMA (ISA)



SBG architecture study underway



Now is the time to engage!
We are soliciting working group participation



Engagement opportunities

- Submit an abstract to an AGU session:
<https://agu.confex.com/agu/fm19/prelim.cgi/Session/75253>
- Contribute to an open-source repository:
<https://github.com/isofit/isofit>
- JPL positions, internships and postdocs:
Spectroscopists, Math / CS backgrounds
- Participate in an SBG working group



With due thanks to:

- **Kevin Bowman** (JPL), for much of the source material in these slides
- **Clive D. Rogers**, for theoretical foundations, approach and notation (e.g. *Inverse Methods for Atmospheric Sounding, Theory and Practice*, 2000).
- **NASA Earth Science** for sponsorship of AVIRIS-NG and the AVIRIS-NG India investigation and analysis.
- **The JPL Research and Technology Development and NASA Center Innovation Fund Programs**
- **The JPL Office of Chief Scientist and Technologist**
- **Other coinvestigators, coauthors and colleagues** including Amy Braverman, Jonathan Hobbs, Robert Spurr, Steven Massie, Bruce Kindel, Manoj Mishra, et cetera.



Backup



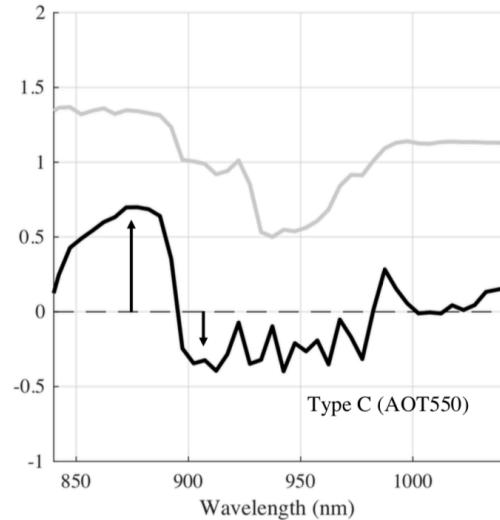
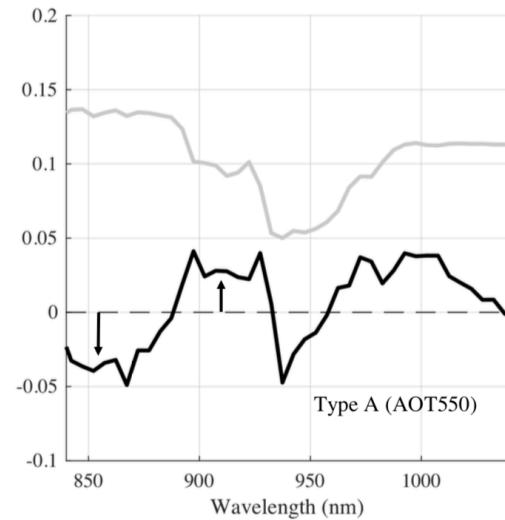
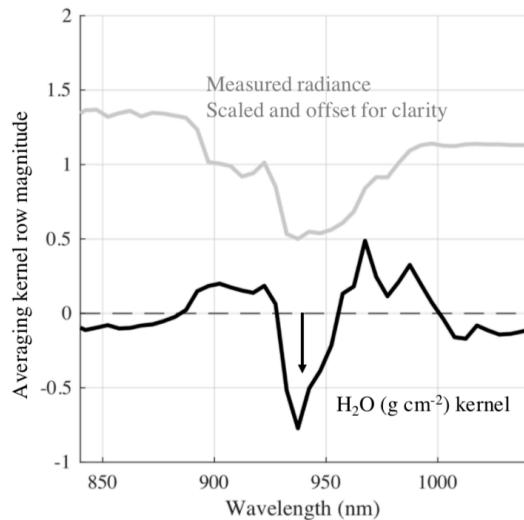
3/10/21

david.r.thompson@jpl.nasa.gov

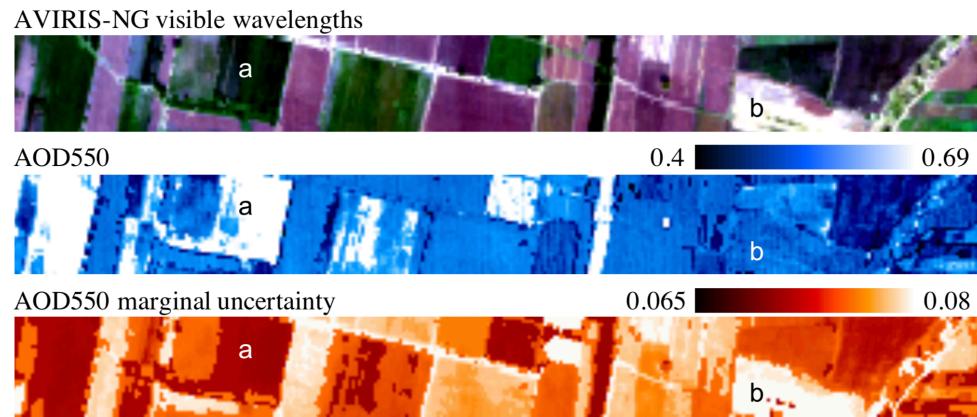
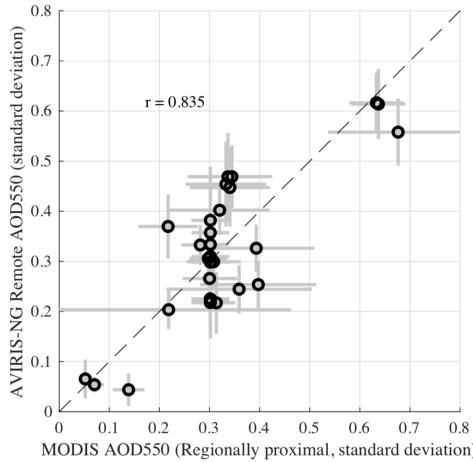
40

High aerosol loading in India campaign

“Averaging Kernels” for H₂O, and absorbing and scattering aerosol particles



High aerosol loading in India campaign



Right: A dataset of 29 flightlines shows uniform improvements in spectral quality metrics vis a vis the AVIRIS-NG standard reflectance product. AOD estimates align with MODIS AOD retrievals from the same day (correlation coefficient $r = 0.83$). Left: different surfaces provide varying levels of aerosol information for the retrieval. Green vegetation is particularly well-constrained. We use the most confident 5% of retrievals to form the flightline-wide estimate.

